CEBAF Program Advisory Committee Nine Proposal Cover Sheet

This proposal must be received by close of business on Thursday, December 1, 1994 at:

CEBAF
User Liaison Office, Mail Stop 12 B
12000 Jefferson Avenue
Newport News, VA 23606

Proposal Title

Search for Free Quarks

Contact Person

Name: David Garelick
Institution: Northeastern University
Address: Physics Department
Address: 111 Dana Research Center
City, State ZIP/Country: Boston, MA 02115, USA
Phone: 617-373-2936 **FAX:** 617-373-2943
E-Mail → Internet: garelick@neu.edu

Experimental Hall: C **Days Requested for Approval:** 1

Hall B proposals only, list any experiments and days for concurrent running:

CEBAF Use Only

Receipt Date: 12/15/94 PR 94-115

By: SP

LAB RESOURCES REQUIREMENTS LIST

CEBAF Proposal No.: ______________________ Date: ______________
(For CEBAF User Liaison Office use only.)

List below significant resources — both equipment and human — that you are requesting *from CEBAF* in support of mounting and executing the proposed experiment. Do not include items that will be routinely supplied to all running experiments, such as the base equipment for the hall and technical support for routine operation, installation, and maintenance.

Major Installations *(either your equip. or new equip. requested from CEBAF)*

NONE

New Support Structures:

Data Acquisition/Reduction

Computing Resources:

New Software:

Major Equipment

Magnets

Power Supplies

Targets

Detectors

Electronics

Computer Hardware

Other

Other

quark 12/14/94

HAZARD IDENTIFICATION CHECKLIST

CEBAF Proposal No.: ______________________ Date: ______________
(For CEBAF User Liaison Office use only.)

Check all items for which there is an anticipated need. Hall C or Hall A spectrometer system

Cryogenics
- ____ beamline magnets
- ____ analysis magnets
- ____ target

type: ________
flow rate: ________
capacity: ________

Electrical Equipment
- ____ cryo/electrical devices
- ____ capacitor banks
- ____ high voltage
- ____ exposed equipment

Radioactive/Hazardous Materials
List any radioactive or hazadorous/ toxic materials planned for use:
____
____
____
____

Pressure Vessels
- ____ inside diameter
- ____ operating pressure
- ____ window material
- ____ window thickness

Flammable Gas or Liquids
type: ________
flow rate: ________
capacity: ________

Drift Chambers
type: ________
flow rate: ________
capacity: ________

Other Target Materials
- ____ Beryllium (Be)
- ____ Lithium (Li)
- ____ Mercury (Hg)
- ____ Lead (Pb)
- ____ Tungsten (W)
- ____ Uranium (U)
- ____ Other (list below)

____
____

Vacuum Vessels
- ____ inside diameter
- ____ operating pressure
- ____ window material
- ____ window thickness

Radioactive Sources
- ____ permanent installation
- ____ temporary use

type: ________
strength: ________

Large Mech. Structure/System
- ____ lifting devices
- ____ motion controllers
- ____ scaffolding or
- ____ elevated platforms

Lasers
type: ________
wattage: ________
class: ________

Installation:
- ____ permanent
- ____ temporary

Use:
- ____ calibration
- ____ alignment

Hazardous Materials
- ____ cyanide plating materials
- ____ scintillation oil (from)
- ____ PCBs
- ____ methane
- ____ TMAE
- ____ TEA
- ____ photographic developers
- ____ other (list below)

____
____

General:

Experiment Class:
- ____ Base Equipment
- ____ Temp. Mod. to Base Equip.
- ____ Permanent Mod. to Base Equipment
- ____ Major New Apparatus

Other: ________
____

BEAM REQUIREMENTS LIST

CEBAF Proposal No.: ______________________ Date: ______________
(For CEBAF User Liaison Office use only.)

List all combinations of anticipated targets and beam conditions required to execute the experiment. (This list will form the primary basis for the Radiation Safety Assesment Document (RSAD) calculations that must be performed for each experiment.)

Condition #	Beam Energy (MeV)	Beam Current (μA)	Polarization and Other Special Requirements (e.g., time structure)	Target Material (use multiple rows for complex targets — e.g., w/windows)	Target Material Thickness (mg/cm²)
1	4000	< 60 μA		(1 cm)^3 carbon	

.e beam energies, E_{Beam}, available are: $E_{Beam} = N \times E_{Linac}$ where N = 1, 2, 3, 4, or 5. For 1995, E_{Linac} = 800 MeV, i.e., available E_{Beam} are 800, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the following additional values of E_{Linac} will become available: E_{Linac} = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence and timing of the available resultant energies, E_{Beam}, will be determined by physics priorities and technical capabilities.

RESEARCH PROPOSAL TO CEBAF

Search for Free Quarks

D. Garelick*, N. Khalil, P. Nistor
Northeastern University
Boston, Massachusetts 02115

W. Oliver
Tufts University
Medford, Massachusetts 02155

and others

Abstract

A conceptually new search for fractionally charged particles, free quarks, is proposed. Unlike all previous experiments, the experiment will be able to detect quarks if: 1) Their interaction length, λ, with normal matter is as small as $\lambda \approx .05\ g/cm^2$; and/or 2) Their energy loss per g/cm^2 is much larger than that expected from just electromagnetic interactions.

The experiment is separated into two phases. In the first phase, this proposal, we will search for negatively charged particles whose apparent momenta are above the beam momentum, if they have integer charge. Such particles must be fractionally charged. The experiment will also be sensitive to such particles even if they have very short interaction lengths with matter. A high momentum magnetic spectrometer (the HMS spectrometer in Hall C) will be used. If such particles are observed, we will propose, in a second phase, to measure their mass/charge ratios.

A measure of the sensitivity of the experiment is as follows. Suppose the quark escapes from the nucleon bag (becomes free) with a probability $PE_q \approx 10^{-3}$ per "hard collision." This corresponds to the best limit placed by previous experiments which searched for quarks with very short interaction lengths (P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989) and L. Lyons, et al., Z. Phys. C **36** 363 (1987).) For $PE_q \approx 10^{-3}$ the

proposed experiment is expected to detect 10^5 quarks per hour. This is more than a factor of 10^4 improvement in sensitivity over the best previous experiment. A request for beam time for this entire exploratory search is 24 hours.

Requests: Phase 1: Electron beam energy = 4000 MeV at 60 μA. Hall C high momentum spectrometer at 30^0 set to 4500 MeV/c with a vacuum chamber from the target surface to the output window of the spectrometer. Carbon target. 24 hours of beam.

* Spokesperson (Garelick@NEU.EDU, 617 373 2936)

Overview

The quark model for explaining the substructure of the hadrons (mesons and baryons) suffers the following major complication. Despite diligent searches, no one has ever seen an free quark.[1)] Thus far, quarks always appear bound inside hadrons. Our proposed experiment explores the hypothesis that single free quarks can sometimes be produced, even though they have escaped detection in all previous experiments. Unlike all previous experiments we will be able to detect free quarks even if:

A) Free quarks have a very strong long range interaction (SLRI) with the normal matter.[2-3)] It has been proposed that the SLRI results from the long range color field carried by the free quark. Due to the SLRI, free quarks might be expected to suffer nuclear interactions in distances as small as $\lambda \approx .05\,\mathrm{g/cm^2}$. A critical new feature of the proposed quark search is that, from the production point of the free quark inside the target to the detector, the path length in material will be $\lambda \leq .05\,\mathrm{g/cm^2}$.

B) The quark energy loss per g/cm^2, dE/dx, is much larger than that due just to electromagnetic, EM, interactions. This is hypothesized to be due, also, to the quark's color field and gives rise to the SLRI. Unlike all other accelerator quark experiments, we do not rely for identification of the quarks on the usual assumption that $dE/dx_{quark} = Q^2\, dE/dx_{EM}$. (Here Q is the ratio of the quark's charge to that of the proton.)

A magnetic spectrometer will be used to select negatively charged particles whose apparent momenta, if they have integer charge, are above the electron beam momentum and thus must be fractionally charged.

To detect free quarks: 1) You have to produce them. 2) The quarks must arrive at the detector and provide the expected signatures above backgrounds. If we are correct, past experiments have produced large numbers of quarks but as a result of possibilities A) and/or B), the quarks were not detected. However, it is likely that quarks with properties A) and/or B) would have been observed in bubble chamber experiments if produced in a high enough abundance. As discussed below, an upper limit estimate of the fraction of bubble chamber interactions giving free quarks possessing a SLRI, without them being detected, is approximately 10^{-3}. (This is approximately the same as the limit obtained by L. Lyons, et al., Z. Phys. C **36** 363 (1987) using magnetic levitation to search for quarks captured on steel spheres.)

Consider the reaction: $\pi^- + p \rightarrow \bar{\mathbf{u}} + \mathbf{d} + \pi^+ + \pi^- + p$, where the π^- falls apart into its constituent anti u, $\bar{\mathbf{u}}$ and $\mathbf{d}$ quarks, with say a 10 GeV π^- beam in a liquid hydrogen bubble chamber. This event would appear to violate the conservation of charge +/- one particles. (The initial and final states differ by one negatively charged particle, a quark, so this event would appear to violate the conservation of charge by one unit of negative charge.) If the quarks have a SLRI interaction, it would not be possible to measure their sign of curvature, charge, in the short .7 cm = $\lambda \approx .05\ \mathrm{g/cm^2}$ path length. Furthermore, similar events without the quark production will produce secondary interactions in the bubble chamber in $\lambda \approx .05\ \mathrm{g/cm^2}$ with a probability of about 10^{-3}, thus further obscuring the quarks. For example, assume 10^4 bubble chamber interactions are examined giving 10 quark events. We believe that these quark events would have been attributed to secondary interactions, impurities in the hydrogen, etc. These arguments, the bubble chamber bound, suggest that in interactions with beam energies $\geq 1\ \mathrm{GeV}$, the probability, P, of a quark escaping, E, in a "hard" collision is: $\mathrm{PE_q} \leq 10^{-3}$. This is to be compared to the sensitivity of our experiment which is better than: $\mathrm{PE_q} \approx 10^{-7}$.

In summary, quark properties A) and B) could explain why all previous counter experiments failed to detect quarks and why bubble chamber experiments and other experiments have missed quarks with $\mathrm{PE_q} \leq 10^{-3}$.

We will propose this experiment in two phases, if Phase 1 is successful. Phase 1 will be a search for negatively charged particles whose apparent momenta are above the beam momentum (and are thus fractionally charged) and have very short interaction lengths with matter. If such particles are observed, in Phase 2, we will propose to measure the mass/charge ratios of such particles.

Phase 1: Search for Fractionally Charged Particles

Kinematics:

We assume that the electron scatters from an unbound **d** quark with M_q = 336 MeV and that this quark is detected at an angle of $\theta_q = 30^0$. For these kinematics: P_q = 1484 MeV/c T_q= 1186 MeV $\theta_e = 15.3^0$ and E_e= 2814 MeV. Here, P_q is the quark's momentum, T_q its kinetic energy and θ_e and E_e are the scattered electron's angle and energy. For charge -1 particles, the spectrometer will be set at 4500 MeV/c.

The Experiment:

A 4000 MeV electron beam will be incident on a $(1\text{cm})^3$ cube of carbon. The magnetic spectrometer will be set to a momentum setting of 4500 MeV/c for charge one particles at an angle of 30 degrees. A beam current of approximately 60 µA will be used. The quark[4)], M_q = 336 MeV and kinetic energy = 1186 MeV , will likely interact in the first .1g/cm^2 of detector material encountered. Furthermore, it is expected that the quark will give up most of its energy to the first 1 g/cm^2 of the detector. Thus, two 1 cm thick scintillators, located and covering the spectrometer focal plane, will measure a large amount of the quark's kinetic energy, say 100 MeV from nuclear spallation. This is to be compared to a minimum ionizing particle that will deposit about 4 MeV. Thus, these scintillators should, by themselves, have good rejection of cosmic rays and accelerator associated backgrounds. In addition, with the quark having 1186 MeV of kinetic energy to loose, several π s should be produced giving tracks in the drift chambers. Such tracks when traced back to their common vertex should indicate that they were produced by a particle traveling up rather than down like a cosmic ray or some of the room background.

The procedure will be to take a series of data runs with the beam intersecting the target [(1 cm)^3 carbon] at varying transverse distances , x_t, into the target as indicated in Fig. 1. As x_t is varied, the quark signal should maximize when the beam intersects the surface of the target facing the spectrometer and the quark signal should essentially disappear when the beam is placed in the center of the target, x_t = 1.2 g/cm^2 and beyond. (See Fig. 2.) Quarks produced at the center of the target should not escape from the target and thus will not be detected.

Phase 1: Sensitivity

In estimating the sensitivity of the experiment, we assume that the nucleons are made up of three point like quarks, loosely energy bound in a bag, about 23 MeV per quark. The sensitivity of the experiment will be expressed in terms of the limits it places on the probability, PE_q, that a quark escapes the nucleon bag after being hit by a scattered electron. The apparatus settings correspond to: the electron scatters from an unbound **d** quark with M_q = 336 MeV and that this quark is detected at an angle of θ_q= 30^0. For these kinematics: P_q = 1484 MeV/c T_q= 1186 MeV θ_e= 15.3^0 and E_e= 2814 MeV. Here, P_q is the quark's momentum, T_q its kinetic energy and θ_e and E_e are the scattered electron's angle and energy. The spectrometer will be set at 4500 MeV/c, for charge -1 particles.

The differential cross-section for electron **d** quark elastic scattering ($e\mathbf{d} \rightarrow e'\mathbf{d}$), from a point like **d** (charge z= -1/3) , is :

$$\left.\frac{d\sigma}{d\Omega}\right)_{e'} = \frac{z^2(e^2/4\pi)^2 \cos^2\Theta/2}{4\,P_0^2 \sin^4\Theta/2\left[1+(\frac{2P_0}{M})\sin^2\Theta/2\right]}$$

$$\text{and} \quad \left.\frac{d\sigma}{d\Omega}\right)_q = \left.\frac{d\sigma}{d\Omega}\right)_{e'} * \frac{P_{e'}}{P_q}$$

For the kinematics indicated above, the quark momentum will be P_q = 1484 MeV/c and the electron momentum will be $P_{e'}$=2814 MeV/c. According to the above, the differential cross-section for elastic electron **d** quark scattering producing a free **d** quark for the kinematics indicated is:

$$\left.\frac{d\sigma}{d\Omega}\right)_q \cong 1.5\text{x}10^{-32}\ \text{cm}^2$$

In addition to assuming an escape probability of PE_q = 1.0, this calculation makes the reasonable assumption that the Fermi motion of the **d** quark inside a nucleon and the motion of the nucleons inside the carbon nucleus can be neglected. (The affects of these assumptions are still being studied.) The sensitivity of the experiment will be expressed in terms of the limit placed on PE_q, the bag penetration probability. For the conditions specified, above, assuming PE_q = 1.0 and 100% detection efficiency for the quark at the focal plane detector array, gives:

$$N_q = (\#e's/sec)*(\#N_q/cm^2)*\left.\frac{d\sigma}{d\Omega}\right|_{eq\rightarrow eq} *\Delta\Omega$$

Here N_q/cm^2 is the number of quarks/cm^2 and $\Delta\Omega = 10$ msr is the spectrometer solid angle. N_q is the number of **d** quarks detected per second under the assumptions stated above.

$$N_q=(0.4\text{x}10^{15})(2.\text{x}10^{24})(1.5\text{x}10^{-32})(10\text{x}10^{-3}) \approx 1.2\text{x}10^5\ /\text{sec}$$
$$\approx 4.3\text{x}10^8\ /\ \text{hour}$$

In the calculation, directly above, we have not taken into account several effects which could reduce the sensitivity of the experiment. First, for quarks with a SLRI, absorption with $\lambda \approx .05\ g/cm^2$ corresponds to λ = 200 μm path length in the carbon target. In Fig. 2 we show the fraction, F_q, of quarks produced taking into account beam that misses the target (beam sigma = 100 μm), beam position (X_0) and the quark absorption length in carbon, lambda. For lambda = 200 μm, X_t= -50 μm, this gives F_q= .3 . For a quark detection efficiency, DEff, of 80 % this gives:

$$N'_q = F_q \times DEff \times N_q \approx 10^8 \text{ / hour},$$

where N'_q is the number of quarks detected per hour, under the stated assumptions.

To transform this result into an actual sensitivity limit on PE_q, requires a knowledge of the background of particles with quark signatures in the focal plane "quark" detectors as well as the actual quark detection efficiency. We guestimated, above, a detection efficiency of 80%. (This will be investigated by measurements of elastic ep scattering where a proton of kinetic energy equal to the quark's kinetic energy interacts in an absorber placed at the location of the spectrometer's exit vacuum window.) Suppose the quark escapes from the nucleon bag with a probability $PE_q \approx 10^{-7}$. For two three hour runs (one at the surface and one at the center of the target) this could give a 30 quark signal above background. (Hopefully, investigation of the actual backgrounds can be made in the near future.) The beam positioning for these two runs is indicated in Fig. 2. However, a more realistic request for beam time is four times this example, namely 24 hours in order to measure at other beam positions, etc.

{Another type of background we have considered is caused by atoms like negatively charged deuterium: a deuteron with two electrons attached. Such an atom, with 1484 MeV/c momentum would be formed by the deuteron picking up the two electrons as it leaves the target. This background will have a weak dependence on the transverse position of the beam and thus be identifiable as background. In addition, this atom will deposit fixed amounts of energy in the detector, unlike the quarks. We presently believe that this type of background is negligible, but it is still being examined.}

Phase 2: Measuring the Quark Masses

Phase 2 will be carried out only after Phase 1 successfully finds evidence for fractionally charged particles. Furthermore, the actual beam energy and spectrometer settings for Phase 2 will be determined by the energy and angle dependencies of the quark production determined in Phase 1. Phase 2 measures the free quark mass/charge ratio by using the time of flight technique to measure the velocity of particles traversing a known magnetic field, as described below. The zero time for the quark time of flight will be determined by measuring electron-quark coincidences. The details of the electron detector will depend critically on the results of Phase 1. The discussion given here, Phase 2, is to present the reader with a possible method for determining the mass/charge ratios.

For a fixed magnetic field setting, the bending angle Θ_B is given by:

$$\Theta_B = \frac{c_o QB}{P}$$

where c_o = spectrometer magnetic length
Q = charge of the particle
B = average magnetic field strength
P = particle's momentum and

$$P = \frac{M*v}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

where M = mass of the particle
v = the particle's velocity
c = the velocity of light

Let $P_1 = \frac{c_o*B}{\Theta_B}$ and $\frac{t}{t_o} = \frac{c}{v}$,

Here P_1 is the momentum of a charge 1 particle bent by Θ_B, the central spectrometer trajectory. t= the time of flight of the particle and t_o is the time of flight of a particle traveling at the speed of light.

It follows that: $\left(\frac{M}{Q}\right)^2 = P_1^2\left[\left(\frac{t}{t_o}\right)^2 - 1\right]$

and the uncertainty in the $(M/Q)^2$ determination is:

$$\delta\left(\frac{M}{Q}\right)^2 = 2P_1^2\sqrt{\left[\left(\frac{t}{t_o}\right)^2 - 1\right]^2\left(\frac{\delta P_1}{P_1}\right)^2 + \left(\frac{t}{t_o}\right)^2\left(\frac{\delta t}{t_o}\right)^2}$$

For the CEBAF spectrometers we assume: $\frac{\delta P}{P} = \pm 0.02$ and $\delta t = \pm .25$ nsec where the momentum resolution depends on the ability to measure the quark's position at the focal plane. The quark flight path from the target to the detector is about 24 m for the Hall C HMS spectrometer. Fig. 3 indicates the $(M/Q)^2$ resolutions by the vertical error bars on the $(M/Q)^2$ points. These calculations have been done for P_1 = 4500 MeV/c as an illustration of the technique. (Since the electron beam energy will be 4000 MeV, all negatively charge 1 particles will not have enough energy to pass through the spectrometer.) To be more complete, we have also shown the calculations for: u and d quarks $M_d = M_u$ =336 MeV, for the s and c quarks M_s = 538 MeV and M_c=1500 MeV, for a light d' quark $M_{d'}$ = 5 MeV and for the π meson M_π=140 MeV. Clearly the resolutions would improve at lower beam and quark momenta if the cross sections are large enough.

References

1) P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989), L. Lyons, Phys. Reports **129** , 225 (1985) and M.Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982)

2) D. Garelick, Phys. Rev. **D19** (1979) 1026

3) A. De Rujula, et al., Phys. Rev. **D17** (1978) 285

4) A. De Rujula, et al., Phys. Rev. **D12** (1975) 147

Fig. 1. Beam targeting. With the beam in position Beam 2, quarks are expected to be produced at the surface and be detected by the spectrometer. For position Beam 1, nearly all the quarks produced are expected to interact and be absorbed in exiting the target. The spectrometer will be set at 30^0, in the direction shown for the quark in the diagram.

TOP VIEW OF CARBON TARGET

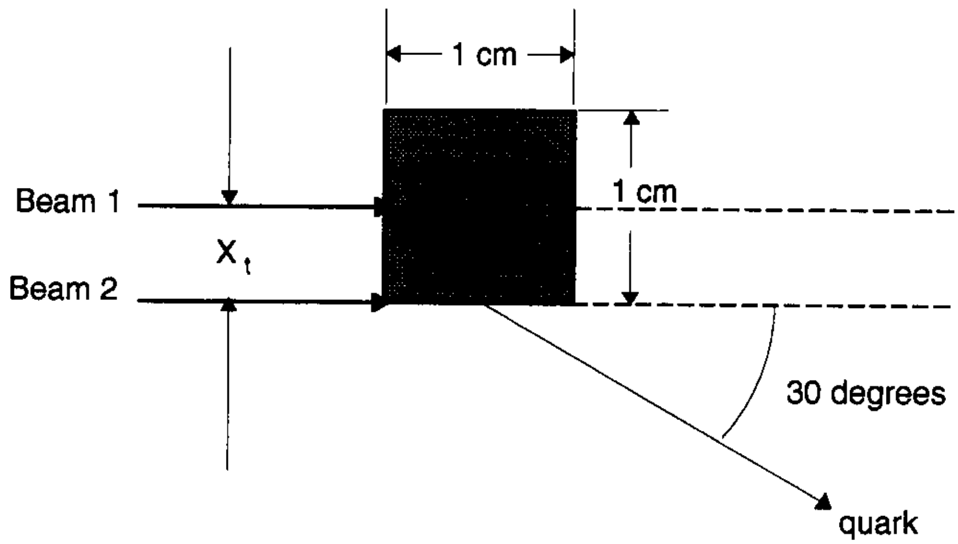

Fig. 2. The fraction, F_q , of quarks produced taking into account beam that misses the target (beam sigma = 100 μm), beam position (X_t) and the quark absorption length in carbon, lambda is plotted. For lambda = 200 μm, X_t= -50 μm, this gives F_q= .3 .

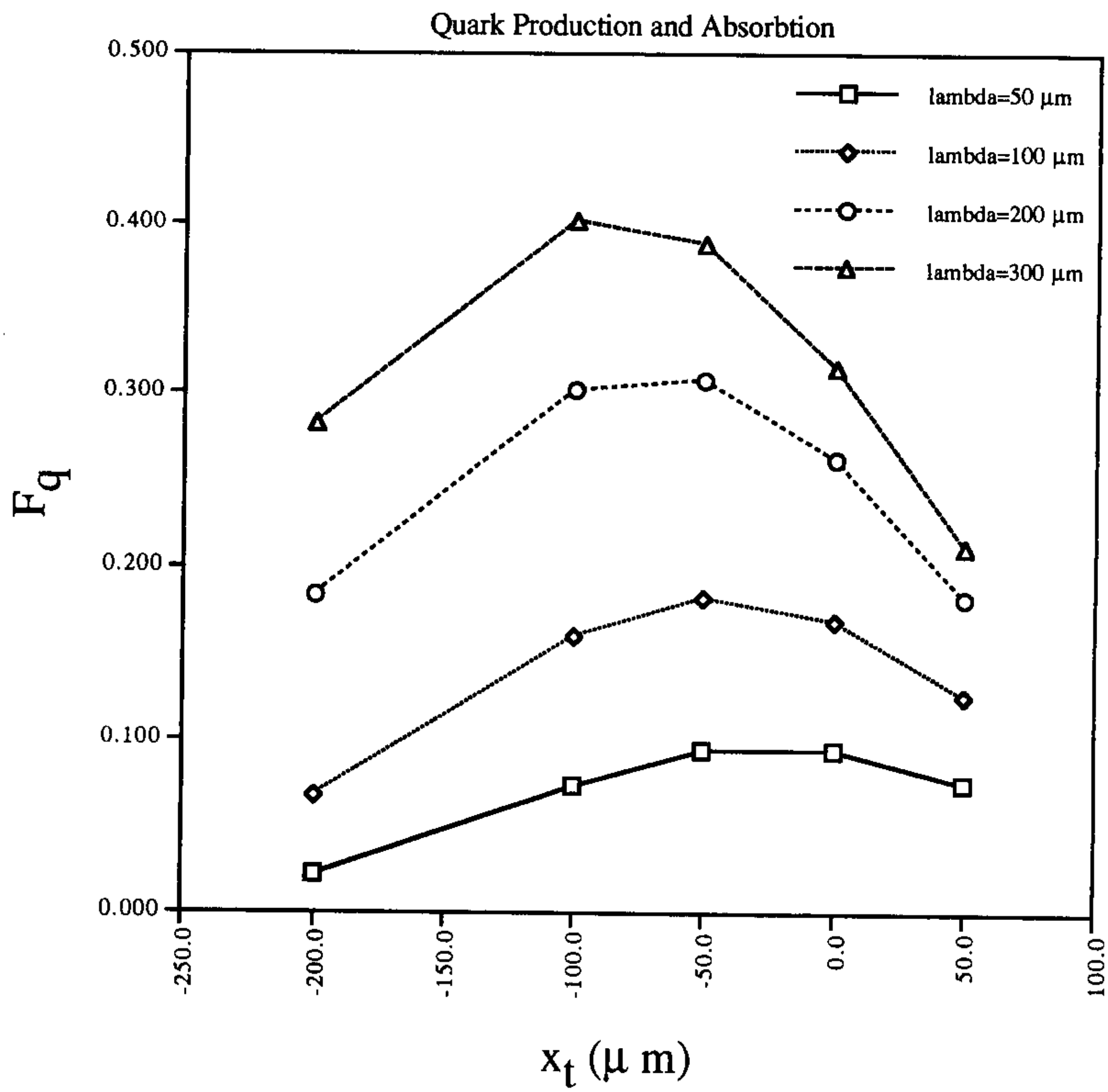

Fig. 3. Resolutions in $(M/Q)^2$ indicated by the vertical error bars in a $(M/Q)^2$ versus M plot. For additional details, see text.