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 Narrow Excited States of the Proton

Contact Person

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Experimental Hall: C* Days Requested for Approval: 2

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

* Hall A would be OK, too.

CEBAF Use Only

Receipt Date: 12/11/95 PR 95-006

By: γ

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

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 A or Hall C spectrometer syste[m] with 10 cm lqd. H2 target

Cryogenics	Electrical Equipment	Radioactive/Hazardous Materials
___ beamline magnets ___ analysis magnets ___ target type: ______ flow rate: ______ capacity: ______	___ cryo/electrical devices ___ capacitor banks ___ high voltage ___ exposed equipment	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	300	< 60 μA		10 cm lqd. H2	
2	4000	< 60 μA		10 cm lqd. H2	

ʼhe 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} a 00, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the followi dditional values of E_{Linac} will become available: E_{Linac} = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence ar iming of the available resultant energies, E_{Beam}, will be determined by physics priorities and technical capabilities.

RESEARCH PROPOSAL TO CEBAF

Search for Narrow Excited States of the Proton

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and others

Abstract

We propose a measurement of the reaction $e+p \rightarrow e'+X$ to search for narrow excited states of the proton , p*, in the mass region:

$$M_p < M_x < M_p + 1250 \text{ MeV}$$

The sensitivity of the proposed measurements is more than a factor of 50 better than in previous experiments. We will use the Hall C HMS spectrometer to measure the scattered electron, e', at a 12.5° angle. Beam energies of .3 GeV and 4 GeV and a maximum beam current of 60 μA are proposed, for a total of 50 hours. The experiment will use a 10 cm long liquid hydrogen target. The use of this thin walled target, together with the expected spectrometer resolutions and beam resolutions will provide excellent missing mass resolution. With very high sensitivity, at the lower beam energy, .3 GeV, the mass region $M_p < M_x < M_p + 140$ MeV will be covered. At the higher beam energy, 4. GeV, the mass region $M_p < M_x < M_p + 1250$ MeV will be scanned with very good sensitivity.

An indication of the proposed experiment's sensitivity is that any narrow state, p*, will be detected if its cross section relative to elastic scattering is greater than $2x10^{-5}$ in the region $M_p < M_x < M_p + 140$ MeV. There is a suggestion, by R. P. Feynman, concerning the possible existence of a colored proton, p_c, at a mass of about 990 MeV. In terms of coupling constants, this p_c is expected to be detected if the color carrying part of the photon has a strength α_c, relative to the electromagnetic coupling constant α_{EM}, of $\alpha_c / \alpha_{EM} \geq 2x\,10^{-5}$.

Requests: The Hall C HMS spectrometer operated for high resolution for electron measurements. Beams of a maximum current of 60 μA at .3 GeV and 4 GeV, each for 24 hours. 10 cm liquid hydrogen target. (This experiment might be run simultaneously with the proposed experiment: Search for Direct Conversion of Electrons into Muons)

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

Motivation

The primary motivation for this proposal is the principle that experiments should be done whenever a dramatic improvement in sensitivity is possible over previous studies in a region of "physics phase space" of special interest. The conjecture, presented below, is discussed to point out such a region of special interest and the proposed experiment has a sensitivity of better than a factor of 50 over previous experiments.

The quark model, with color, has been very successful in explaining many features of hadron spectroscopy.[2)] In its basic form, the baryons, are made up of three quarks bound together by the exchange of gluons. Each of the quarks inside the physical baryon has a different color and the total color is zero. In this model, a physical proton is considered to be made up of two u quarks and a d quark. The simplest analysis of the proton and neutron magnetic moments implies[2)] that the masses of the u and d quarks are :

$$M_q \cong M_u \cong M_d \cong 336 \text{ MeV}$$

It follows that the binding energy, E, of the three quarks in the physical proton is :

$$E = 3M_q - M_p = 3(336) - 938 \cong 70 \text{ MeV}$$

or each quark-quark bond, B, can be considered to give rise to a binding energy E_B of :

$$E_B \cong E/3 \cong 23 \text{ MeV}.$$

Using this model, let us consider the properties of a physical hadron (colored proton) , p^*, made up to two u quarks and a d quark, where two of the quarks have the same color. These quarks inside the p^* will have two attractive bonds and one repulsive bond. If one assumes, in analogy to electrostatics, that the interaction energy of two like colored quarks is the opposite of the interaction energy for two unlike colored quarks in the same state, one estimates:

$$M_{p^*} \cong 3(336) - 23 \cong 985 \text{ MeV}.$$

R. P. Feynman's[1] calculation used group theory to calculate the p* mass with the result: $M_{p^*} \cong 990$ MeV. Other calculations[3] based on $M_q \cong M_u \cong M_d \cong 363$ MeV give $M_{p^*} \cong 1039$ MeV.

Obviously, the p* mass is not predicted exactly, even though the above model suggests that: $M_p < M_{p*} < M_p + 140$ MeV. Generally the width of the p* state will probably be very narrow , $\Gamma < .1$ MeV, since it is expected to decay into a gamma and a proton. However, if the p* is high enough in mass to decay into a proton and a colored π, it probably would not be narrow. Since very little is known about colored π s, we will not speculate further, other than to say the entire p* mass region accessible at CEBAF should be searched with high sensitivity. Fortunately, such a search will take relatively little beam time, about 2 days.

In summary: the main importance of the above arguments is that they provide a plausibility argument for the existence of a narrow excited proton. At a minimum, the proposed experiment will search the CEBAF mass region for new excited states of the proton with greatly improved sensitivity over prior experiments.

The Experiment for $M_p < M_{p*} < M_p + 140$ MeV

The physical background, in this mass region, is the radiative tail of elastic ep scattering. The calculations, below, are estimates of the sensitivity of the proposed experiment, which is determined by the size of the radiative tail and the missing mass resolution δM_X. The calculations, presented, are for $M_{p^*} \cong 985$ MeV and the results for other masses are given at the end of the proposal. As we shall show, our methods are in excellent agreement with actual data provided to us by K. Dow.[4]

We plan to use the Hall C HMS spectrometer to detect the scattered electrons at 12.5° . We will use the Hall A liquid hydrogen target, 10 cm length, "beer can" geometry with the beam traveling along the can's axis, .008 in Al walls. The Al windows each of have 2.3×10^{-3} radiation lengths, r.l. For an incident beam energy E_e = 300 MeV and a scattering angle of 12.5°, the elastic scattered energy is $E_{el} \cong 298$ MeV. As discussed below, the level of the radiative tail is set by the total number of radiation lengths, X_o, seen by the scattered electron[5] and by the elastic scattering cross section. X_o has three pieces:

$$X_o = X_{o.t.w.} + X_{o.l.h.} + X_{o.i.b.}$$

where $X_{o.t.w.}$ = the number of radiation lengths in the target windows = $4.6x10^{-3}$

$X_{o.l.h.}$ = the number of radiation lengths in the liquid hydrogen = $11.6x10^{-3}$.

$X_{o.i.b.}$ = the number of equivalent radiation lengths[5] when the electron scatters elasticly in the field of the proton = $3.0x10^{-2}$

Thus, the total equivalent radiation length is: $X_o \cong 4.6x10^{-2}$.

The counting rates and estimates of the sensitivity of the experiment are calculated following the methods of L. W. Mo and Y. S. Tsia[5] and are as follows:

Let N_R be the number of electrons per second, in a bin of width Γ_E in the radiative tail. Here Γ_E is the full width half maximum of the measurement uncertainty in the missing mass, M_X. To a good approximation[6]:

$$N_R \cong \frac{\Gamma_E X_o}{2*(E_{el} - E_{e'})} * \left[(E_{el}/E_{e'})^2 + 1\right] * N_{el}$$

where: $N_{el} = (\#e's/sec)*(\#p's/cm^2)*\frac{d\sigma}{d\Omega}\Big|_{ep\to ep} * \Delta\Omega$. Here $\frac{d\sigma}{d\Omega}\Big|_{ep\to ep}$ is the elastic scattering cross section and $\Delta\Omega$ is the HMS solid angle. N_e = is the number of elastic scatterings detected by the HMS under the same running conditions. (See Ref. 6 for the above relationship expressed in terms of the cross sections.)
E_{el} = 298 MeV is the scattered energy at the elastic peak and $E_{e'}$ = 250 MeV is the scattered electron energy at M_x = 985 MeV.

Γ_E has four parts: $\Gamma_E = \Gamma_\Theta \oplus \Gamma_{El} \oplus \Gamma_{Eb} \oplus \Gamma_I$, where $\oplus$ implies that the terms are added in quadrature. Here: Γ_Θ = the gaussian resolution, full width, contribution to the uncertainty of the M_X measurement due to the scattering angle measurement uncertainty. Γ_{El} = the resolution contribution from the measurement of the energy loss, E_{El}, the difference between the scattered electron's energy, $E_{e'}$ and incident beam energy, E_b. We plan to achieve $\Gamma_{El} = .001\ E_{e'}$. Γ_{Eb} = is the contribution from the beam energy spread where we plan to achieve Γ_{Eb} = .0001 or better. Γ_I = the resolution from the variation in energy loss by ionization due to different path lengths in the target.

For the kinematics given above:

$$\Gamma_E = \Gamma_\Theta \oplus \Gamma_{El} \oplus \Gamma_{Eb} \oplus \Gamma_I$$

$$\Gamma_E = 0.205 \oplus 0.246 \oplus 0.000 \oplus 0.000$$

$$\Gamma_E = 0.32 \text{ MeV}$$

(More complete details of these calculations are given following the References in the back of this proposal titled: "Calculation of the mass resolution." Also, similar calculations for carrying out the experiment using the a HRS spectrometer in Hall A gives: Γ_E=0.21 MeV. Thus, the sensitivity of the HRS would be a factor of 1.5 better than for the HMS in Hall C, as indicated below.)

$$\text{Thus,} \quad N_R \cong 4.1 \times 10^{-4} * N_{el}$$

$$\text{and } N_{el} = (\#e's/sec)*(\#p's/cm^2)*\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep} *\Delta\Omega\ .$$

The 10 cm diameter liquid hydrogen target, a beam current of .6μA, an HMS angular acceptance $\Delta\Omega$ = 10 msr and $\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep} = 3.9\times10^{-28}\ cm^2/sr$, gives:

$$N_{el} = (0.4\times10^{13})(0.4\times10^{24})(4\times10^{-28})(10^{-2}) = 0.6\times10^{7}\ /sec.$$

Thus, $N_R = (4\times10^{-4})*(0.6\times10^{7}) \cong 2.4\times10^{3}$ counts/(second Γ_E)

If we require that the p^* signal appear at least 5% above the radiative tail and be at least a 5 standard deviation affect, it follows that:

$$\frac{N_{p^*}}{N_R} \geq 5x10^{-2} \text{ and } N_R \geq 10^4.$$

To accumulate 10^4 counts per Γ_E bin, for the setting indicated above, requires less than 1 minute, even at a beam current of .6 μA. For these parameters, the total scattered electron event rate at the focal plane will be approximately $2x10^4$ per second. This will probably saturate the data handling capabilities of the HMS. For a scan of 25 magnet settings of 20 minutes each, this implies a total beam time of 8 hours. Taking various inefficiencies into account, we conservatively ask for 24 hours.

It also follows that:

$$N_{p^*} \geq (5x10^{-2})*(4x10^{-4})*N_{el}=2x10^{-5}*N_{el}$$

if this p^* is to be detected in this experiment. This defines the sensitivity of the experiment for M_{p^*} = 985 MeV.

We get the cross section limit of $\frac{\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep^*}}{\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep}} \geq 2x10^{-5}$.

If the p^* form factor is the same as the proton, it follows that:

$\frac{\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep^*}}{\left.\frac{d\sigma}{d\Omega}\right|_{ep\to ep}} \cong \frac{\alpha_c}{\alpha_{EM}}$. Thus, our experiment typically requires $\left(\frac{\alpha_c}{\alpha_{EM}}\right) \geq 2x10^{-5}$ for the detection of a p^* in the mass region to be measured.

The sensitivity calculations, above, apply to the special kinematics case of where the beam energy is E_B=300 MeV, the scattering angle is 12.5° and M_{p^*}=985 MeV. The results of the calculations for the full mass region to be covered at E_B=300 MeV are given in Figs.1 through 3. It is assumed that the momentum acceptance of the HMS is 10%. Our plan is to change the magnet current in 5% steps (50% overlap) accumulating at least 10^4

events per Γ_E for each magnet setting. Thus, each mass bin of width Γ_E will contain at least 10^4 events for each of two magnet settings and there will be good overlap between the adjacent magnet settings.

A Check On Our Calculations

The measurements of K. Dow[4)] at a beam energy of 289 MeV and an angle of 54^{O} at Bates are shown in Fig. 3 along with our calculations. There are no free parameters in these calculations. The excellent agreement between Dow's measurements and the calculations indicates that our method for calculating the radiative tail is reliable. Furthermore, the elastic peak in Dow's data has Γ_E = 0.90 MeV, in agreement with our calculations.

Limits Set By Previous Experiments

The best previous experiments known to us are the works of K. Dow[4)] and A. Esaulov, et al.[7)] neither of which was designed to search for narrow states. However, both experiments did measure some of the mass region of interest. We estimate that the sensitivity of our proposed experiment is better than a factor of 50 more than that of K. Dow and more than a factor of 150 better than that of A. Esaulov, et al.

Additional Remarks

1) It is of interest to compare the above sensitivity limit to the limit implied by the agreement between the measured Z^0's width and its width predicted from the Standard Model. The Z^0 width has been measured to $\pm 1.0\mathrm{x}10^{-2}$ GeV.[8)] If the Z^0, the heavy photon, has a colored piece, this will broaden the Z^0 beyond the Standard Model value. Thus, from the Z^0 decay width (LEP Experiments) one gets: $\frac{\delta\Gamma}{\Gamma} \approx \frac{1.0\mathrm{x}10^{-2}}{2.487} \approx .4\mathrm{x}10^{-2} \geq \frac{\alpha_c}{\alpha_{EM}}$.

Our experiment is sensitive to: $\alpha_c / \alpha_{EM} \geq 2x\,10^{-5}$ or nearly a factor of 200 more sensitive to a colored photon than the limits suggested by the Z^0 width.

The Experiment for $(M_p + 140 \text{ MeV}) < M_{p*} < (M_p + 1250 \text{ MeV})$

As discussed before, the mass of the p* cannot be predicted exactly. Therefore, we wish to scan the full mass region accessible at CEBAF. In this higher mass region the "background" is not the radiative tail but rather the scattering of electrons from the lowest lying N* states. For this scattering the ratio of the cross section for the N* scattering, in an interval Γ_E, in MeV, to the elastic ep scattering is approximately:[9),3)]

$$R(N^*/ep) = \Gamma_E/270$$

The sensitivity of our experiment versus Mx, derived from the above using the method developed for the lower mass radiative tail background, is presented in Fig. 4.

References

1) R. P. Feynman, Les Houches, Session XXIX, (1976)

2) A. De Rujula, et al., Phys. Rev. D 12 (1975) 147

3) D. J. Griffiths, Introduction to Elementary Particles, John Wiley & Sons, Inc. (1987)

4) Measurements made by K. Dow at Bates as part of her Ph. D. thesis research (unpublished.) We thank K. Dow for making the results of these measurements available to us.

5) L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41 (1969) 205

6) This formula $N_R \cong \frac{\Gamma_E X_o}{2*(E_{el} - E_{e'})} * \left[(E_{el}/E_{e'})^2 + 1\right] * N_{el}$ can be arrived at in the following way. First, one uses the approximation of L. W. Mo and Y. S. Tsia[5] in which the interaction, bremsstrahlung, is approximated in two parts. One part in which the incident electron sees one half of the total radiation lengths, $X_o/2$, before it scatters and one part in which the electron scatters and then sees one half of the total radiation lengths. The first term of the above expression is the standard bremsstrahlung expression. The first term inside the brackets corresponds to beam bremsstrahlung followed by elastic scattering. This term is bigger than one since the degraded beam electron has a larger elastic cross section than does the electron at beam energy. The second term inside the brackets is just the bremsstrahlung after the beam electron has scattered elasticly.

The above formula, in terms of the cross sections, is:

$$\frac{\Gamma_E d\sigma}{d\Omega dM_X} \cong \frac{\Gamma_E X_o}{2*(E_{el} - E_{e'})} * \left[(E_{el}/E_{e'})^2 + 1\right] * \frac{d\sigma}{d\Omega_{el}}$$

7) A. S. Esaulov, et al., Nuc. Phys. B136 (1978) 511

8) Particle Data Group, Phys. Rev D11 (1992)

9) P.L. Pritchett, et al., Phys. Rev. 184 (1969)1825

Calculation of the mass resolution.

Now calculate the mass resolution:

First,the energy loss determination:

$$\Gamma El_j := \frac{1}{M_j} \cdot (Mp + Eb \cdot (1 - \cos(\theta))) \cdot .001 \cdot E_j$$

Second, the variation in energy loss due to differing path lengths in the target:

$$\Gamma l_j := \frac{1}{M_j} \cdot (Mp + Eb \cdot (1 - \cos(\theta))) \cdot .00$$

Third, the effect of the spread in the beam energy:

$$\Gamma Eb_j := \left(\frac{1}{M_j}\right) \cdot (Eb + E_j) \cdot (1 - \cos(\theta)) \cdot (.0001 \cdot Eb)$$

Fourth, the scattering of incident beam, b:

The quantities indicated by deltas are rms.

$$Xin := .0081 \qquad Xout := .0081$$

$$\delta\theta b := \frac{13.6}{Eb} \cdot \sqrt{Xin} \cdot (1 + .038 \cdot \ln(Xin))$$

Fifth, the scattering of outgoing electron of energy E_j:

$$\delta\theta E_j := \frac{13.6}{E_j} \cdot \sqrt{Xout} \cdot (1 + .038 \cdot \ln(Xout))$$

Combine the two angles:

$$\delta\theta total_j := \sqrt{\delta\theta b^2 + (\delta\theta E_j)^2}$$

$$\delta\theta mrad_j := 1000 \cdot \delta\theta total_j$$

$$\Gamma\theta_j := \frac{1}{M_j} \cdot Eb \cdot E_j \cdot \sin(\theta) \cdot \delta\theta total_j \cdot 2.36$$

$$\Gamma total_j := \sqrt{(\Gamma\theta_j)^2 + (\Gamma El_j)^2 + (\Gamma Eb_j)^2 + (\Gamma l_j)^2}$$

Fig. 1. Mass resolution versus mass at 300 MeV, 12.5°.
The units are MeV.

p* 300/12.5 deg

$$\Gamma total_j := \sqrt{(\Gamma\theta_j)^2 + (\Gamma El_j)^2 + (\Gamma Eb_j)^2 + (\Gamma I_j)^2}$$

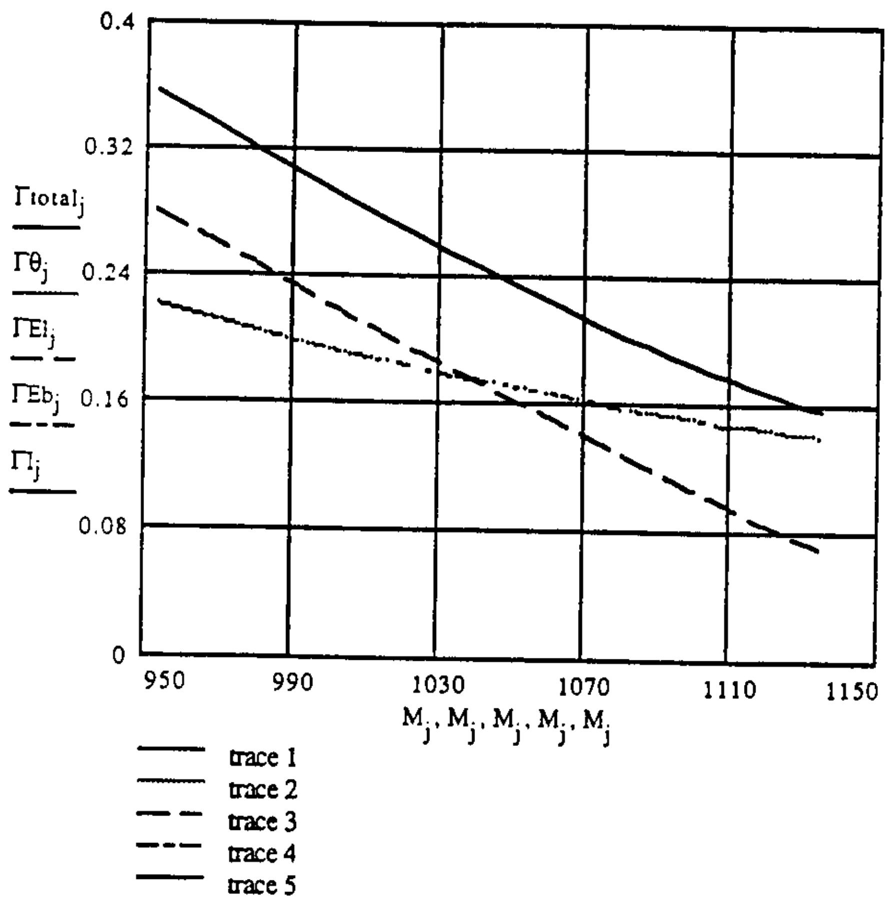


Fig. 2. Cross section sensitivity, relative to elastic scattering, versus mass in MeV at 300 MeV 12.5°.

$$Xotot := Xin + Xout + 1.5 \cdot \frac{1}{137 \cdot 3.14} \cdot \left(\ln\left(\frac{QSQ}{.260} \right) - 1 \right) \qquad Xotot = 0.0465$$

$$\Gamma_j := \Gamma total_j \qquad Xo := Xotot \qquad Xofield := Xotot - Xin - Xout \qquad Xofield = 0.0303$$

$$R_j := \Gamma_j \cdot \frac{Xo}{2} \cdot \left(\frac{1}{Ef - E_j} \right) \cdot \left[\left(\frac{Ef}{E_j} \right)^2 + 1 \right]$$

Note, R_j is the probability, per elastically scattered electron, degraded electron ending up in in the bin R_j.

$$S_j := .05 \cdot R_j$$

p* 300/12.5 deg dPb/Pb=.0001 dEe'/Ee'=.001

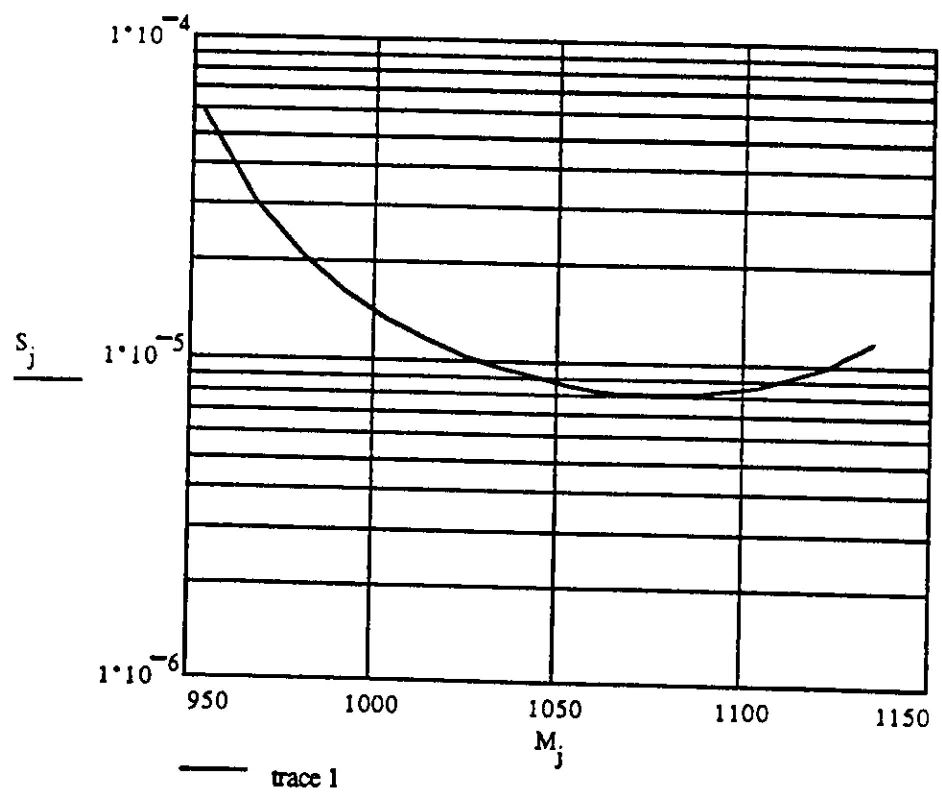


Fig. 3. A comparison of the radiative tail calculations to the measurements of K. Dow. The units of the cross section are nb/(MeV sr). There are no free parameters in the calculation. The mass units are MeV. (289 MeV, 54°.)

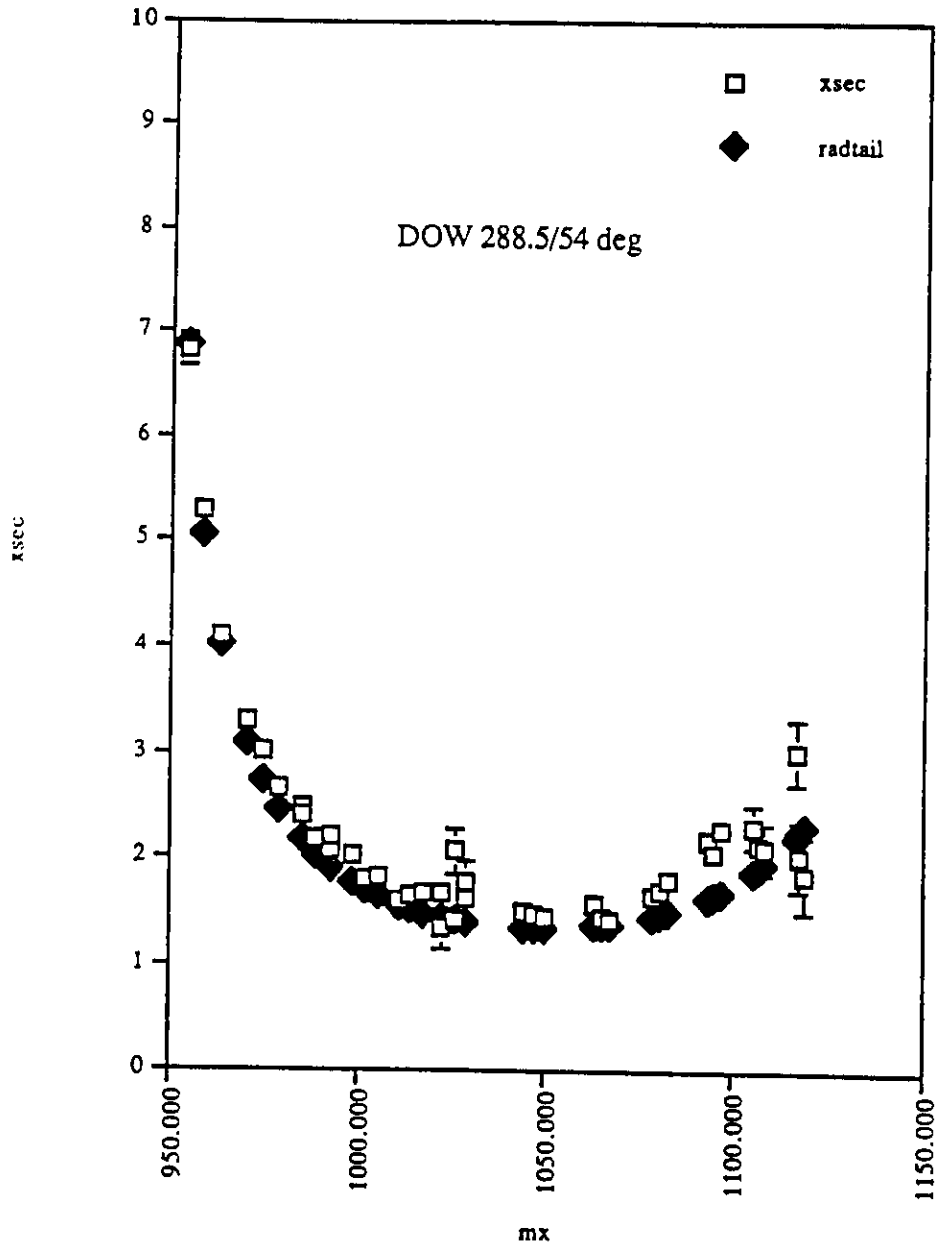
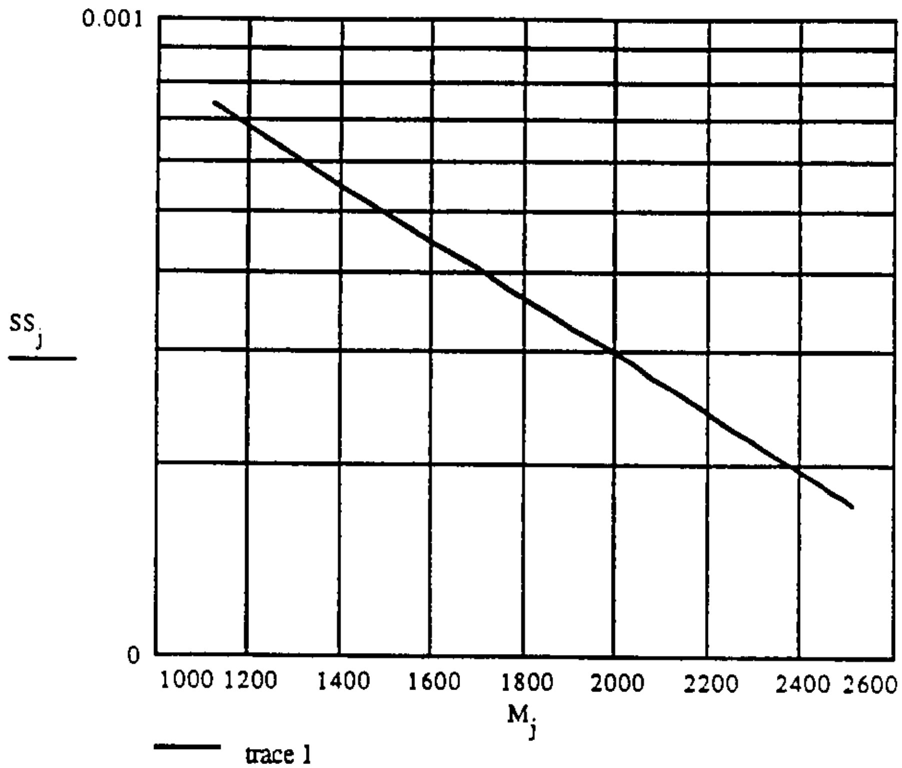


Fig. 4. Cross section sensitivity, relative to elastic scattering, versus mass in MeV at 4000 MeV, 12.5^{o}.

$\Gamma_j := \Gamma total_j$

$RR_j := \frac{\Gamma_j}{270}$

$SS_j := .05 \cdot RR_j$



e→μ 12/14/94

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 Direct Conversion of Electrons into Muons

Contact Person

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Experimental Hall: C* **Days Requested for Approval:** 2

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

* Hall A would be OK, too.

CEBAF Use Only

Receipt Date: ____________________

By: ____________________

e → μ 12/14/94

LAB RESOURCES REQUIREMENTS LIST

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

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

μ detector (under design)

New Support Structures: ____________

Data Acquisition/Reduction

Computing Resources: ____________

New Software: ____________

Major Equipment

Magnets ____________

Power Supplies ____________

Targets ____________

Detectors ____________

Electronics ____________

Computer Hardware ____________

Other ____________

Other

____

c r 12/14/94

HAZARD IDENTIFICATION CHECKLIST

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Check all items for which there is an anticipated need.

Hall C or A spectrometer system wit[h]
10 cm lqd. H2 target

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: ______ ______

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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/cm^2)
1	300	< 60 μA	> 40% polarization, if possible/	10 cm lqd H2	
2	4000	< 60 μA	> 40% polarization, if possible/	10 cm lqd H2	

he 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} a 00, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the followi dditional values of E_{Linac} will become available: E_{Linac} = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence a ming of the available resultant energies, E_{Beam}, will be determined by physics priorities and technical capabilities.

RESEARCH PROPOSAL TO CEBAF

Search for Direct Conversion of Electrons into Muons

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Boston, Massachusetts 02115

W. Oliver
Tufts University
Medford, Massachusetts 02155

and others

Abstract

We propose to search for the lepton number violating reaction: $e^- + p \rightarrow \mu^- + X$ where M_X is in the range: $M_p < M_X < M_p + 1250$ MeV. The highest sensitivity will occur when X is a narrow state, lepto-proton, produced in association with a μ^-. The proposed experiment will extend the search for lepton number violation well beyond the limits of previous experiments by probing for new mechanisims. Longitudinally polarized electron beams, if available, at .3 GeV and 4. GeV will be used. To search for $e^- + p \rightarrow \mu^- + X$ the Hall C HMS spectrometer, at an angle of 12.5°, will scan μ^- momenta corresponding to $M_p < M_X < M_p + 1250$ MeV for the 4. GeV beam and $M_p < M_X < M_p + M_\pi$ for the .3 GeV beam. (The spectrum of M_X could be a continuum and/or have well defined peaks.) Along with the measurements of the mass spectra, the beam polarization will be used to search for evidence of parity violation in the μ^- production. The detection of parity violation, even without a detailed understanding of the level of the backgrounds, would (by itself) be

evidence for a new type of interaction beyond the "Standard Model,"[1] since all expected backgrounds do not violate parity.

For the .3 GeV beam, an indicator of the sensitivity of the experiment (for detecting a narrow lepto-proton) is the ratio, R_B, of background μ^-s, upper limit, to detected elastic ep scattering. At 54^o, an upper limit for R_B of $R_B \approx 1 \times 10^{-6}$ has been shown to be achievable at Bates. Thus, in the proposed experiment direct conversion cross sections should be observable with a sensitivity much greater than $\sigma(ep \rightarrow \mu\, x) \geq 1x10^{-6}\, \sigma(ep \rightarrow ep)$ for $M_p < M_x < M_p + M_\pi$. For $M_p < M_x < M_p + 1250\ \mathrm{MeV}$, at 4. GeV, the calculations are still being refined, but indicate a sensitivity of better than:
$\sigma(ep \rightarrow \mu\, x) \geq 1x10^{-5}\, \sigma(ep \rightarrow ep)$.

Requests: The Hall C HMS spectrometer operated for high resolution with muon detection. Longitudinally polarized beams, if available, of 60 µA at .3 and 4. GeV, each for 24 hours. 10 cm liquid hydrogen target. (This experiment might be run simultaneously with the proposed experiment: "Search for Narrow Excited States of the Proton.")

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

Motivation

The most sensitive searches for µ-->e conversion are:[2] µ− Ti-->e− Ti (µ− conversion in the field of a Titanium nucleus) and the search for the decay $\mu^+ \rightarrow e^+\gamma$. However, these decays could be forbidden if µ-->e conversion is mediated by a lepto-boson carrying both e and µ quantum numbers which converts one of the nucleons to a lepto-nucleon. (The term lepto is used to indicate an object with non zero lepton number.) This possibility provides a strong motivation for the proposed experiment. For example, in this view, the reaction µ− Ti-->e− Ti would be forbidden but the reaction μ^- Ti-->e^- lepto-Ti would be allowed. If the [(lepto-Ti) -(Ti)] mass difference is greater than about 20 MeV, such a conversion process would have, to date, been missed in all previous Ti type experiments. In the proposed experiment, the recoiling nucleon system (lepto-proton) is allowed to have masses, M_X, in the range: $M_p < M_X < M_p + 1250$ MeV. The spectrum of M_X could be a continuum and/or have well defined peaks. We do not know of any previous experiment that directly investigated the proposed reaction mechanism.

Polarized electron beams will be used to search for evidence of parity violation in the μ^- production. The detection of parity violation, even without a detailed understanding of the level of the backgrounds would (by itself) be evidence for a new type of interaction beyond the "Standard Model." All expected backgrounds do not violate parity. (This could be checked, in part, by measuring μ^+ s.)

Experimental Plan

Longitudinally polarized electron beams at .3 and 4. GeV will be used. The HMS spectrometer, at an angle of 12.5°, will scan μ^- momenta corresponding to $M_p < M_X < M_p + 1250$ MeV for the 4. GeV beam and $M_p < M_X < M_p + M_\pi$ for the .3 GeV beam in order to detect the reaction of interest, $e^- + p \rightarrow \mu^- + X$. The kinematics for this reaction are given in Figs. 1 and 2. For μ^- identification, we will require that the particle detected at the HMS focal plain does not produce an electromagnetic shower (is not an electron) for the .3 GeV experiment and for the 4. GeV experiment does not interact in a thick absorber (is not a π.) (The design of this μ identification system is still in progress, but it is presently planned for the 4. GeV experiment that tracking chambers will be used to follow the μ s as they pass through the absorber.) Some results from Bates, using just a "NOT electron" signature from a gas Cerenkov counter, are shown in Figs. 3 and 4. For the 790 MeV data, most of the "NOT electron" signal is probably from π s. At 290 MeV the "NOT electron" signal is probably from Cerenkov counter inefficiency.

Sensitivity of the Experiment
Beam energy = 300 MeV

The dominant source of background is expected to be μ^-s from the decays $\pi^- \to \mu^- + \upsilon$. At the beam energy of 300 MeV, background from the reaction $e^- + p \to e^- + p + \pi^- + \pi^+$ should be zero for the chosen kinematics. The main anticipated backgrounds are from: 1) Electrons which are misidentified and appear as μ s. 2) $\pi^- \to \mu^- + \upsilon$ where the π^- is produced from neutrons in the target walls. 3) π^- s which appear as μ^- s. (The π^-, μ^- separation is still under study.)

The sensitivity is determined in large part by the backgrounds labeled 1) through 3), above. We estimate that background 2) will be much smaller than 1), as a result of identifying μ s that come from the target end windows, using standard spectrometer tracking techniques. Concerning background 1), our estimate, from the experience of others at Bates, is that the electron rejection in the μ signal of 10^4 can be achieved. The calculated sensitivity ratios eμ/ep determined using a 10^2 larger, 1%, electron misidentification are plotted versus M_x for the 300 MeV beam in Figs. 5. (Additional details can be found in the proposal: "Search for Narrow Excited States of the Proton," which might be run simultaneously.)

Considering setup time, etc., a total of 24 hours at this beam energy, should be sufficient.

Sensitivity of the Experiment
Beam energy = 4. GeV

Calculations of the sensitivity at this energy are still being carried out. However, the sensitivity ratios eμ/ep determined by assuming a total background of 1% of the electron rate have been done. The results are given in Fig. 6. (Additional details can be found in the proposal: "Search for Narrow Excited States of the Proton," which might be run simultaneously.)

Considering setup time, etc., a total of 24 hours at this beam energy, should be sufficient.

Search for Parity Violation

The principle is that backgrounds: μ s from π decay and electrons come from interactions of the beam and the target(s) which obey parity. Thus, an longitudinal polarization asymmetry dramatically above that expected from the weak interactions, about 10^{-6}, will indicate a new type of interaction.

For the purpose of making estimates of the asymmetry, A, in the cross sections, for the two longitudinal beam polarizations (+, -): $A = \frac{(N_+ - N_-)}{P(N_+ + N_-)}$, where P is the polarization of the beams and the N s are the number of events measured with each of the polarized beams. It follows that the fractional uncertainty in the measurement of A is: $\frac{\delta A}{A} = \frac{1}{PA\sqrt{N_+ + N_-}}$. For P = 40%, A =1, $N_{total} = N_+ + N_- = 625$ detected μ s, $\frac{\delta A}{A} = 10\%$. If the lepton number violating reaction, e-->μ, takes place at a significant level with respect to the backgrounds and it has a large parity violation, a new interaction beyond the "Standard Model" could "easily" be discovered.

References

1) For example: D. J. Griffiths, Introduction to Elementary Particles, John Wiley & Sons, Inc. (1987)

2) Particle Data Group, Phys. Rev D50 (1994)

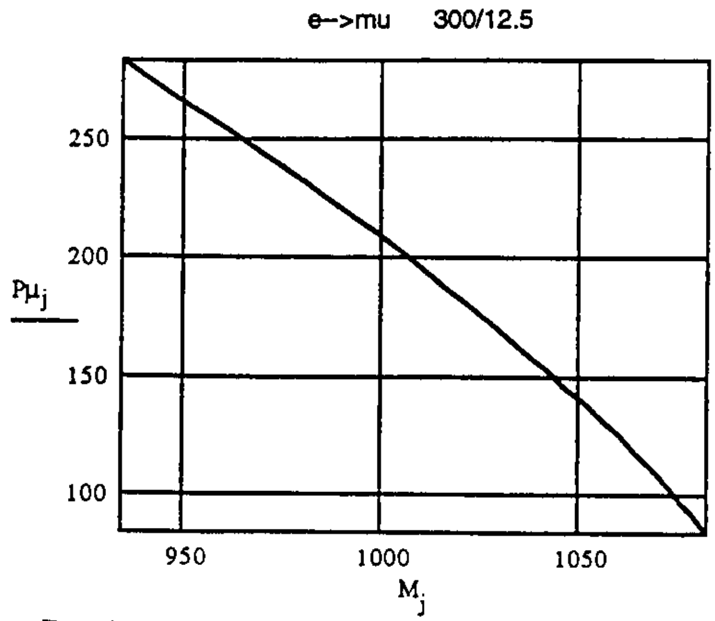


Fig. 1. $P\mu_j$ is the μ's momentum (MeV/c), and M_j is the mass of the X system (MeV) in ep->μX for the .3 GeV experiment.

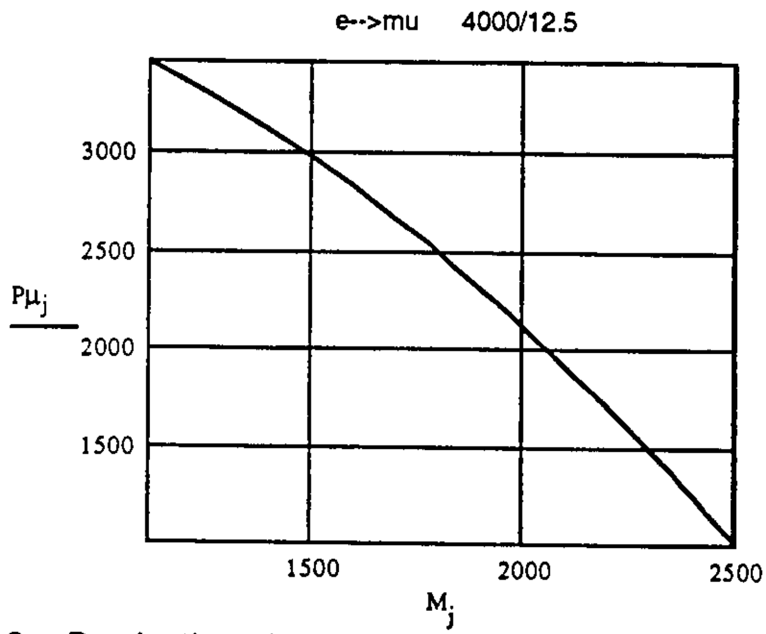


Fig. 2. $P\mu_j$ is the μ's momentum (MeV/c), and M_j is the mass of the X system (MeV) in ep->μX for the 4. GeV experiment.

Fig. 3. Results from Bates at 290 MeV and 54°. The radiative tail (calculation) and the measured electron cross section and the (NOT electron)/electron ratio are plotted. (log plot)

G 288/54 Xsec pi/e rad tail 12/12/94

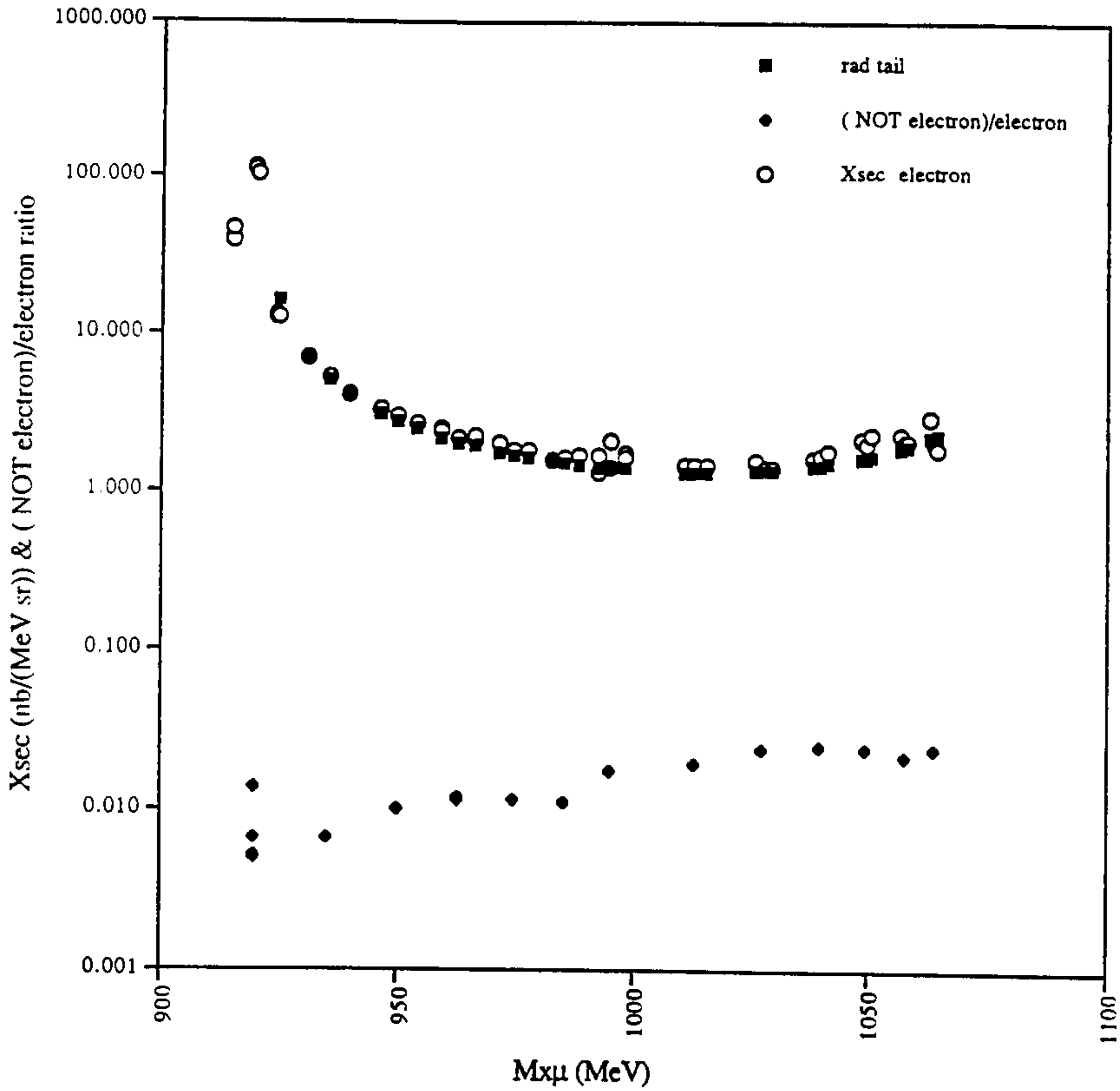


Fig. 4. Results from Bates at 790 MeV and 54^{0}. The electron and NOT electron cross sections as well as the calculated radiative tail are plotted. The N*(1236) is very evident. The NOT electron cross section is a mixture of: misidentified electrons, π s and μ s. (log plot)

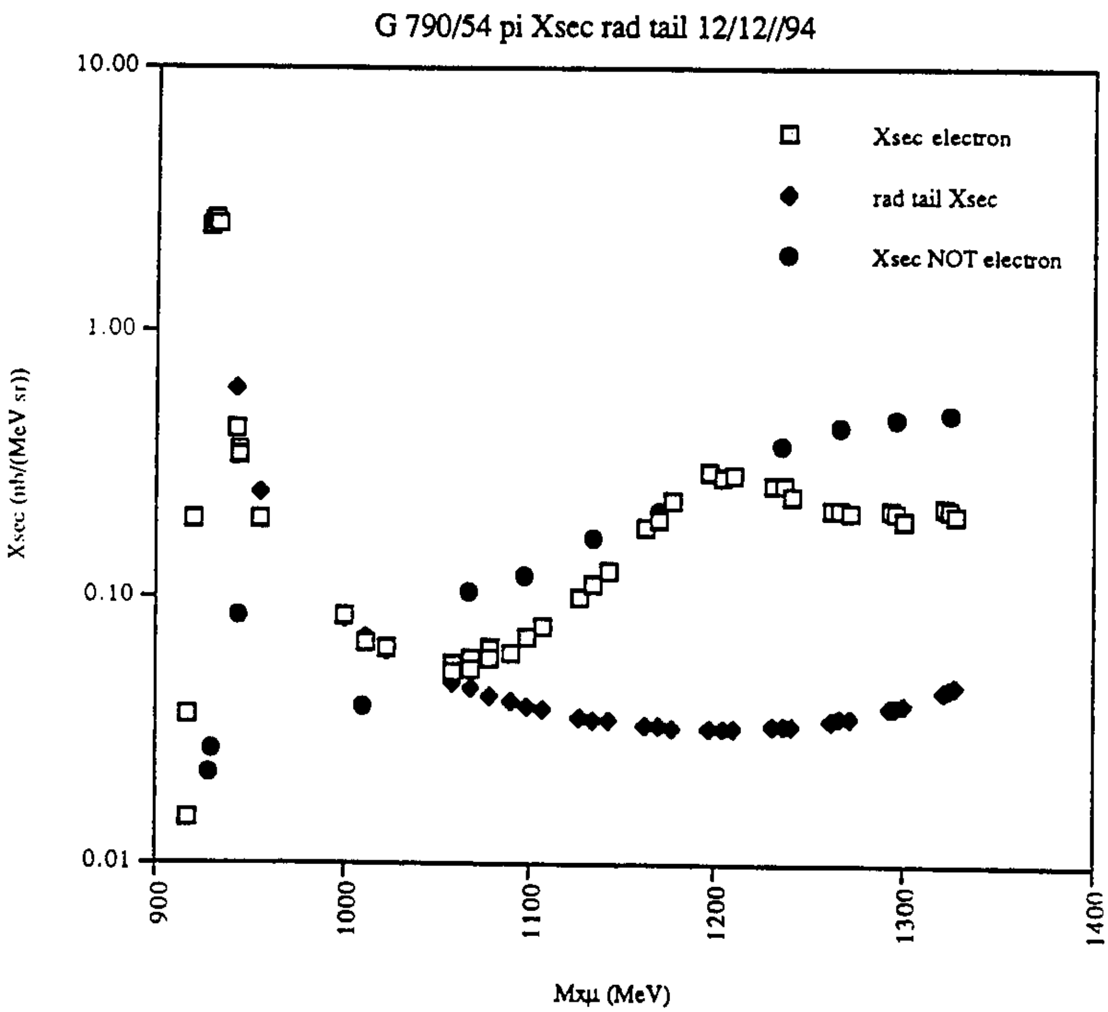


Fig. 5. Sensitivity of the .3 GeV experiment. S_j is the cross section sensitivity, 5 std/ 5% signal (ep->μX)/(ep->ep). M_j is the mass (MeV) of the narrow X system in ep->μX.

$$Xotot := Xin + Xout + 1.5 \cdot \frac{1}{137 \cdot 3.14} \cdot \left(\ln\left(\frac{Q^2 \cdot 10^6}{.260} \right) - 1 \right) \qquad Xotot = 0.047$$

$$\Gamma_j := \Gamma total_j \qquad Xo := Xotot$$

$$R_j := \Gamma_j \cdot \frac{Xo}{2} \cdot \left(\frac{1}{Ef - E_j} \right) \cdot \left[\left(\frac{Ef}{E_j} \right)^2 + 1 \right]$$

Note, R_j is the probability, per elastically scattered electron, of the degraded electron ending up in in the bin R_j.

$$S_j := R_j \cdot 10^{-2}$$

Beam energy = 300 MeV 12.5 degrees 1.0 % of radiative tail.

Sj is the the cross section sensitivity, 5 std/5.0% signal (e-->mu) / (ep-->ep).

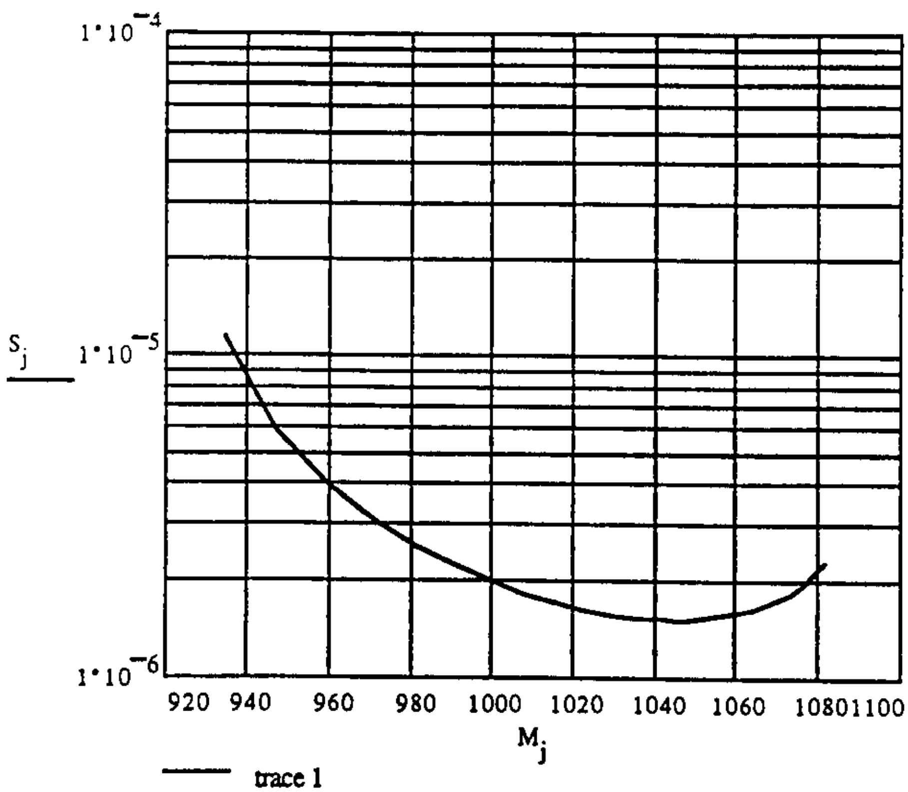
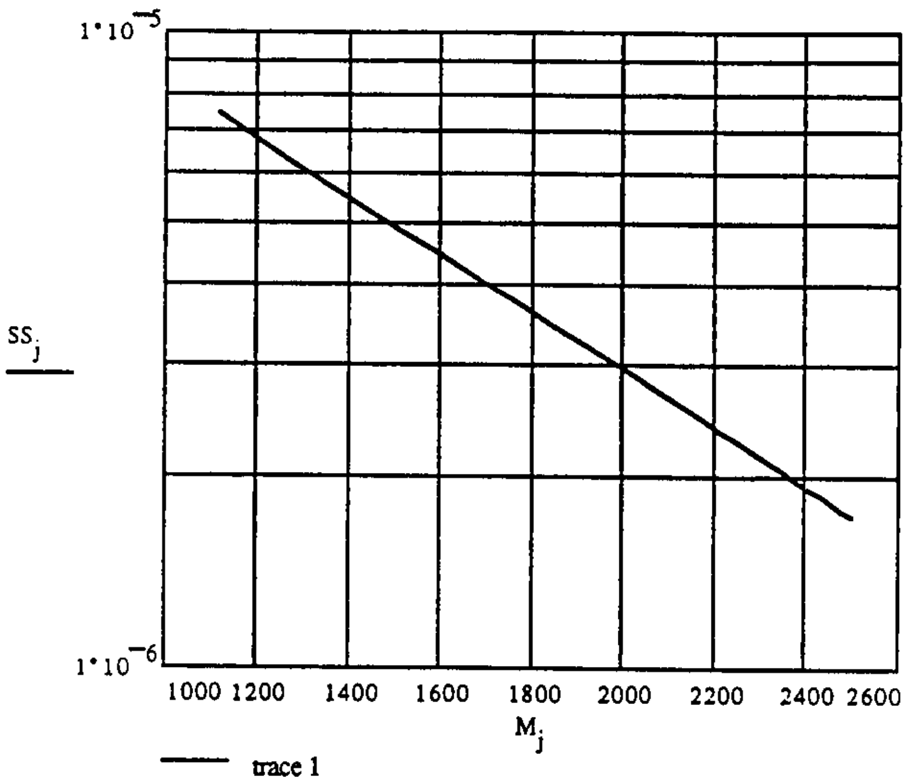


Fig. 5. Sensitivity of the 4. GeV experiment. SS_j is the cross section sensitivity, 5 std/ 5% signal (ep->μX)/(ep->ep). M_j is the mass (MeV) of the narrow X system in ep->μX.

$\Gamma_j := \Gamma total_j$ 4000/12.5 e-->mu

$$RR_j := \frac{\Gamma_j}{270}$$

$$SS_j := .05 \cdot .01 \cdot RR_j$$



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
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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: __________

By: __________

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

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/cm^2)
1	4000	< 60 μA		$(1\ cm)^3$ carbon	

The 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} 300, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the follow additional values of E_{Linac} will become available: E_{Linac} = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence 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

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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 $\lambda \approx .05\ \mathrm{g/cm^2}$; 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 $\lambda \approx .05\, g/cm^2$. 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 $\lambda \leq .05\, g/cm^2$.

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: $\pi^- + p \rightarrow \bar{u} + d + \pi^+ + \pi^- + p$, where the π^- falls apart into its constituent anti **u**, $\bar{u}$ and **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 = $\lambda \approx .05\ g/cm^2$ path length. Furthermore, similar events without the quark production will produce secondary interactions in the bubble chamber in $\lambda \approx .05\ g/cm^2$ 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 ≥ 1 GeV, the probability, P, of a quark escaping, E, in a "hard" collision is: $PE_q \leq 10^{-3}$. This is to be compared to the sensitivity of our experiment which is better than: $PE_q \approx 10^{-7}$.

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 $PE_q \leq 10^{-3}$.

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 $(1cm)^3$ 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 ($ed \rightarrow e'd$), 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:

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

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:

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

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.

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

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 $\lambda \approx .05\ \text{g}/\text{cm}^2$ corresponds to $\lambda = 200$ 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:

$$\Theta_B = \frac{c_o Q B}{P}$$

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.

<u>References</u>

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

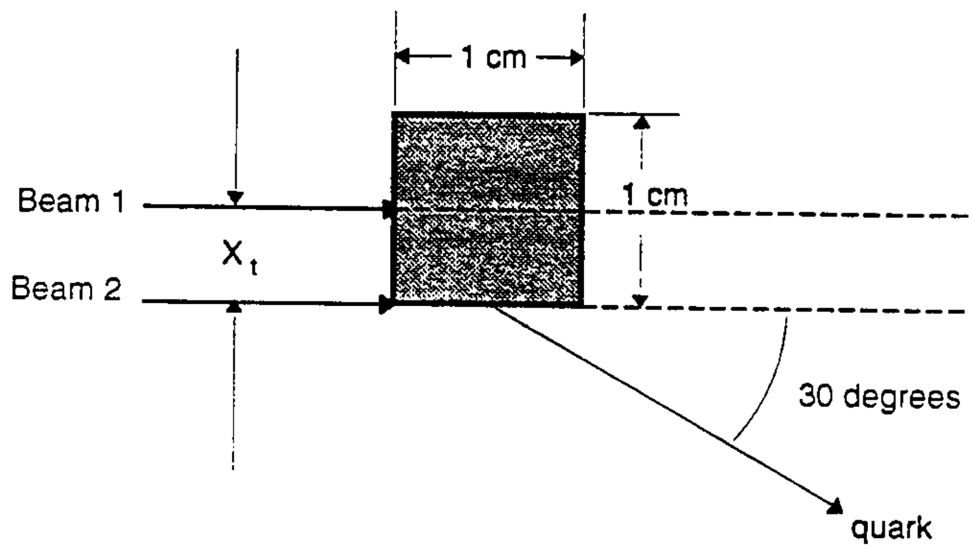


Fig. 2. The fraction, F_q , of quarks produced taking into account beam that misses the target (beam sigma = 100 μm), beam position (X_t) and the quark absorption length in carbon, lambda is plotted. For lambda = 200 μm, X_t= -50 μm, this gives F_q= .3 .

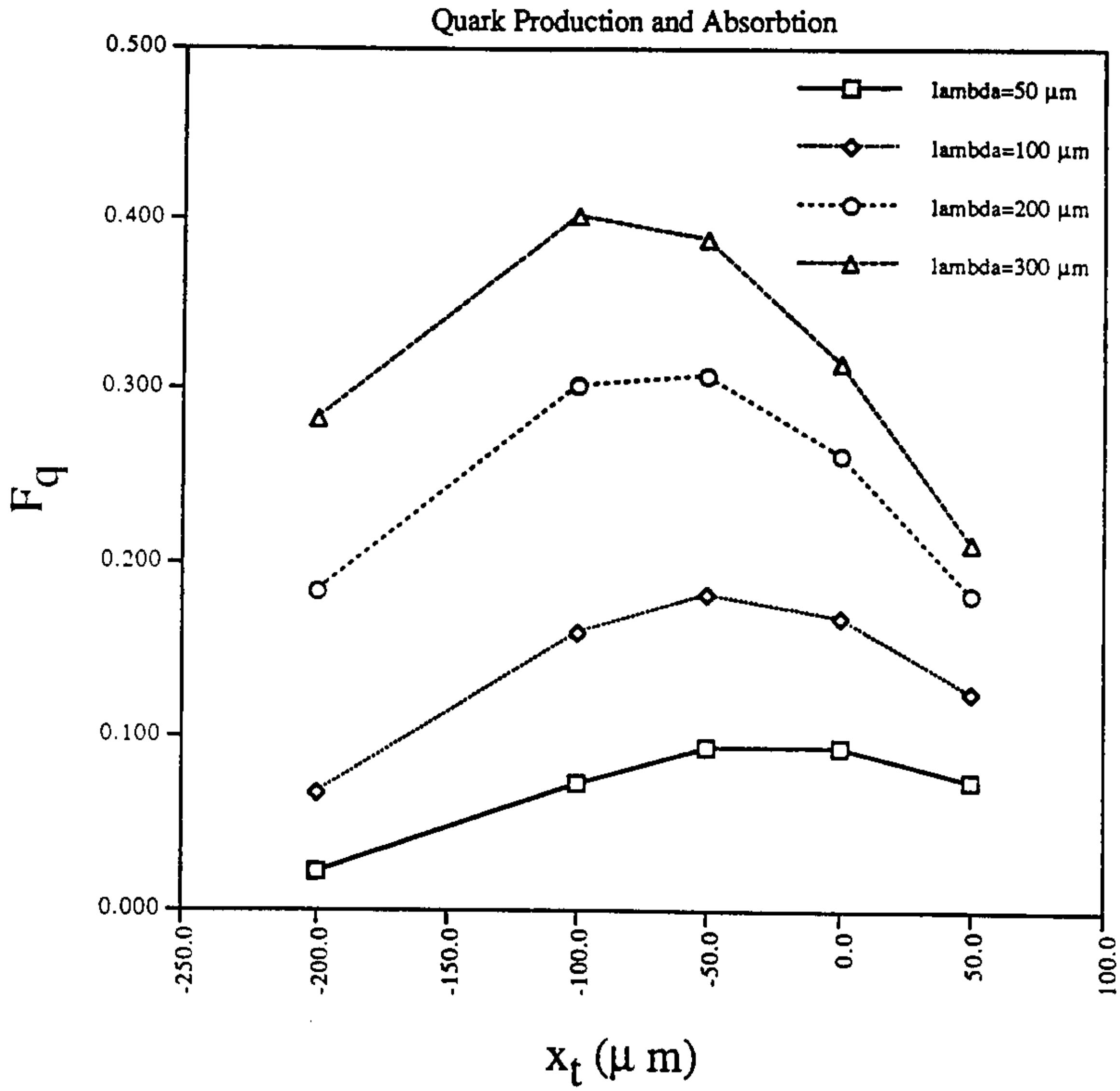
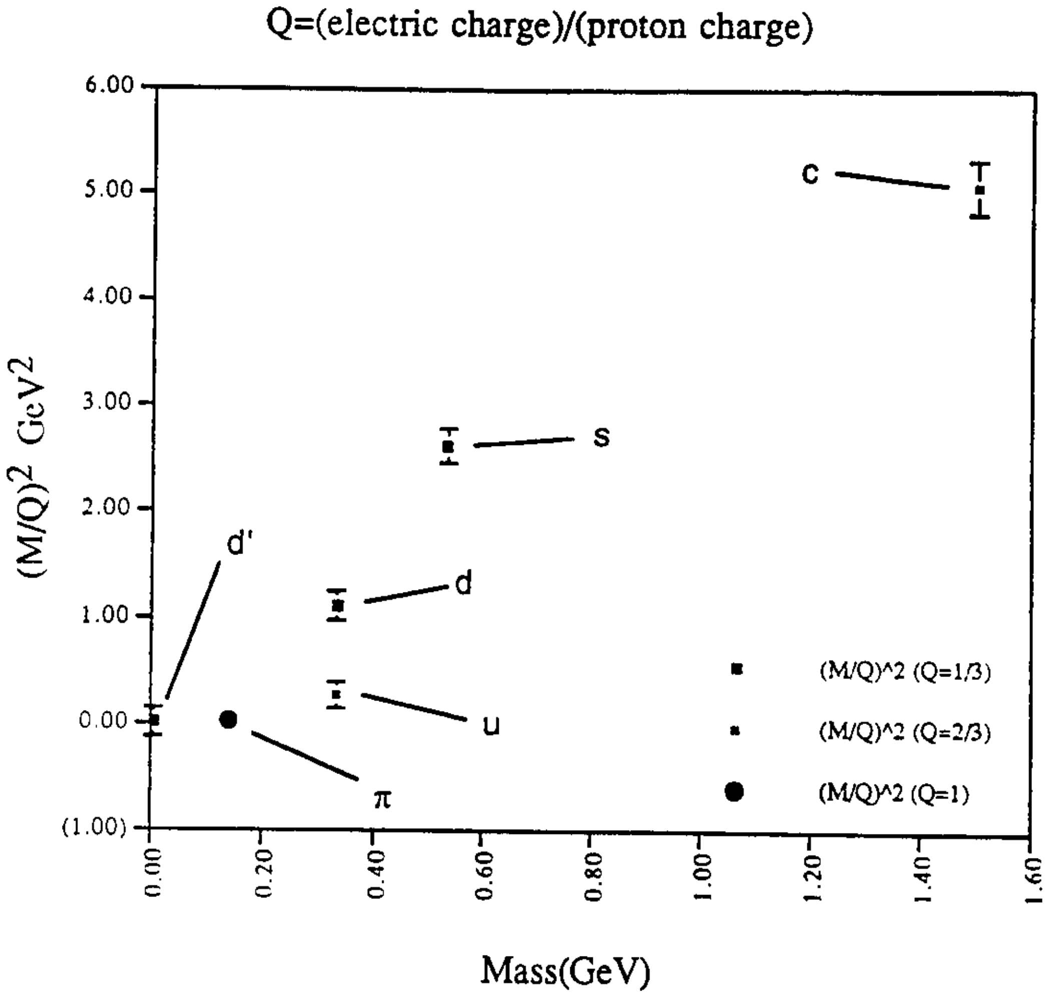


Fig. 3. Resolutions in $(M/Q)^2$ indicated by the vertical error bars in a $(M/Q)^2$ versus M plot. For additional details, see text.



Appendix D

Proposal: PR-94-113, Hall C
Spokesperson: D. Garelick
Title: Search for Narrow Excited States of the Proton

Motivation:

The objective of this proposal is to search for a narrow excited state of the proton. It was suggested that color octet states would occur at higher mass than a color antisymmetric state. The excited, "color-charged" proton would then be surmised to decay by a "color-charged" photon.

Measurements and Feasibility:

The experiment is straightforward electron scattering from the proton similar to experiments which have been performed as either calibrations or studies of the proton at all electron scattering laboratories. Energy resolution is likely to be important since the proposed process is likely to have a vanishingly small width.

Issues:

The physics arguments for an excited proton state with color were not convincing.

Although some Bates data were presented, the PAC was not convinced that already existing data from recent experiments at SLAC and other electron scattering laboratories were considered in setting present limits.

Recommendation:

Reject.

Proposal: PR-94-114, Hall C
Spokesperson: D. Garelick
Title: Search for Direct Conversion of Electrons into Muons

Motivation:

The purpose of the proposed experiment is to search for the conversion of electrons to muons by exchange with a proton of a hypothetical particle carrying both electron and muon flavor quantum numbers.

Measurements and Feasibility:

This experiment would measure muons with the HMS spectrometer in Hall C at beam energies of 0.3 and 4 GeV. The detector package in the HMS is not presently configured to detect muons. No details are given regarding muon detection. No convincing case has been made for the effective elimination of background muons.

Issues:

The implications of the existence of the postulated particles on known processes have not been comprehensively examined. The proposed experiment is extremely difficult to perform convincingly. even at the level of sensitivity indicated. This proposal is inconsistent with the level of accuracy required for such an experiment.

Recommendation:

Reject.

Proposal.: PR-94-115, Hall C
Spokesperson: D. Garelick
Title: Search for Free Quarks

Motivation:

This proposal would search for the production of free quarks from a carbon target. The focus of the search is for quarks that have a very strong long range interaction and may have escaped detection.

Measurements and Feasibility:

The proposal suggests that the standard HMS spectrometer and detector package would be used for the search. The spectrometer would be set at a momentum above the beam momentum (for charge = -1) to observe the fractional charge.

Issues:

A detailed comparison with existing searches and the relative sensitivities was not presented. The PAC is not convinced that the standard detector package of the HMS is useful for this search.

Recommendation:

Reject.