Search for Top Quark and a Test of Models without Top Quark up to 38.54 GeV at PETRA

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With a PETRA energy scan in ≤30-MeV steps, the continuum production of open top quark up to 38.54 GeV is excluded. Over regions of energy scan from 29.90 to 38.63 GeV limits are set on the product of hadronic branching ratio and electronic width $B_h\Gamma_{ee}$ for toponium to be less than 2.0 keV at the 95% confidence level. By a search for flavor-changing neutral currents in b decay, models without a top quark are excluded.

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With the discovery of J (Ref. 1) and Υ (Ref. 2) quark-antiquark states and the resulting increase in understanding of high-energy physics, there is great interest in the possibility of the existence of a new quark flavor, called top, associated with a heavy quark of charge $\frac{2}{3}e$. Measurements up to 36.72 GeV have not revealed either the bound toponium state or the open top threshold.[3,4] There are now many theoretical models explaining why top has not been found at such high energies. These models can be classified into two groups: (1) Top exists at heavier mass. Included in some of these models[5] is the prediction that the open top threshold should exist around 38 GeV. (2) Top does not exist. In these models[6] the bottom quark is in a weak isospin singlet (or an isospin triplet) and decays weakly by a flavor-changing neutral current to another charge-$\frac{1}{3}e$ quark plus a fermion-antifermion pair.

We report the results of a search for the open top threshold up to PETRA center-of-mass energy $\sqrt{s} = 38.54$ GeV. We also report on the search for flavor-changing neutral current of the b quark by looking for its $\mu^+\mu^- + X$ decay.

Since the increase in the maximum energy of PETRA, the MARK-J detector[7] has taken data in an energy scan up to 38.63 GeV in $\Delta(\sqrt{s}) \leq 30$ MeV steps (compatible with PETRA machine energy resolution) in a search for enhancements of cross section in the process

$$e^+e^- \to (\gamma) \to \text{hadrons}. \tag{1}$$

Events from reaction (1) are selected[7] by requiring that (a) the total visible energy E_{vis} is more than 50% of the c.m. energy; (b) the measured energy is balanced within 60% of E_{vis} in both longitudinal and transverse directions with respect to the beam line; and (c) the shape of the shower development in the layer structure of the detector is incompatible with a purely electromagnetic nature for the final state.

The acceptance for reaction (1) has been calculated with a Monte Carlo simulation which provides a phenomenological model of hadron production processes based on perturbative quantum chromodynamics (QCD).[8] The model incorporates q^2 evolution and weak decays of heavy quarks in the fragmentation process and also includes the effects of initial-state photon bremsstrahlung corrections to order α^3.[9] The accep-

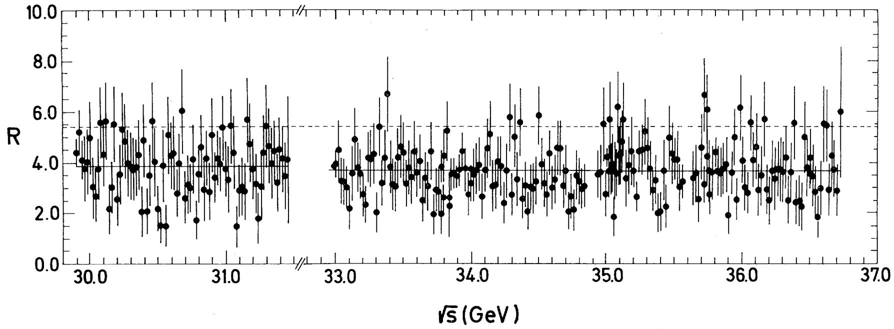

FIG. 1. The relative hadronic cross section R as a function of $\sqrt{s}$ with range 29.90 to 36.72 GeV. The dashed line shows the QCD prediction with continuum production of u, d, s, c, b, and charge-$\frac{2}{3}$ top quarks. The solid line is the mean value of R calculated from the data points.

tance is about 87% and is independent of $\sqrt{s}$.

The quantity R, defined as the ratio of the total hadron production cross section to the pointlike QED cross section,

$$R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{\text{point}}, \tag{2}$$

has been measured by use of the number of hadron events which remain after application of all corrections and background subtractions.

Background contributions from the two-photon process

$$e^+e^- \to e^+e^- + \text{hadrons} \tag{3}$$

and from τ decays,

$$e^+e^- \to \tau^+\tau^- \to \text{hadrons} + X, \tag{4}$$

were calculated by use of Monte Carlo techniques. The total subtraction was $\Delta R \simeq 0.2$.

Figure 1 summarizes the measurements of R during the first energy scan covering the ranges 29.90 to 31.46 GeV and 33.0 to 36.72 GeV. With an average luminosity of ~40 nb^{-1} per point we obtain a mean value of $R = 3.76 \pm 0.05$. Figure 2 shows the results from the second scan from 37.94 GeV to the maximum PETRA energy of 38.63 GeV with an average luminosity of ~60 nb^{-1} per point and a mean value of $R = 3.91 \pm 0.19$ at an average energy of 38.29 GeV. The errors shown are statistical and we estimate a systematic error of 6% due to the model dependence of the acceptance, event selection criteria, and measurement of luminosity. The data are consistent with the prediction of QCD for u, d, s, c, and b quarks, namely $R \sim 3.88$. Figure 3 shows the normalized thrust distribution $N^{-1}dN/dT$ for the data in the range 37.94 to 38.63 GeV. The thrust

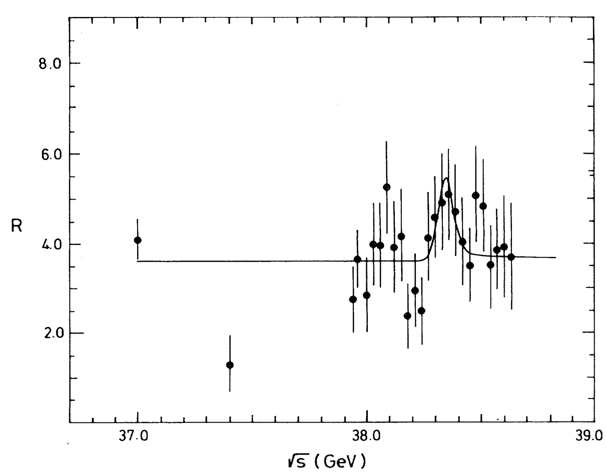

FIG. 2. The relative hadronic cross section R as a function of $\sqrt{s}$ in the range 37 to 38.63 GeV. The curve is the best fit to the largest deviations found in the entire scan.

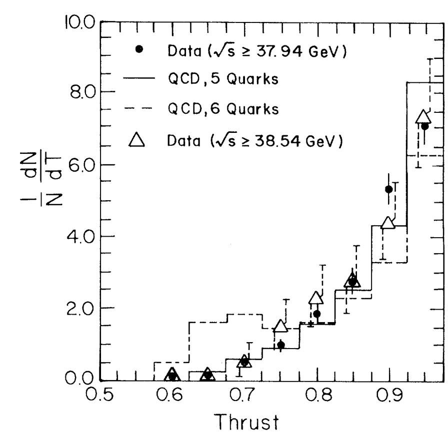

FIG. 3. The thrust distributions for events in the range $37.94 \leq \sqrt{s} \leq 38.63$ GeV and in the range $38.54 \leq \sqrt{s} \leq 38.63$ GeV. The solid curve is the expectation for five quark flavors and the dashed curve is that for six flavors.

distribution is consistent with predictions of QCD Monte Carlo for five-flavor production.

If massive open top-quark pairs were produced we would expect to observe an enhancement of the number of events at low thrust[7] as well as an increase in R by $\frac{4}{3}$ units to $R = 5.3$. The highest energy points in our energy scan, $38.54 \leq \sqrt{s} \leq 38.63$ GeV, give an average $R = 3.75 \pm 0.51$. Independently, the thrust distribution in this energy region is shown (Fig. 3) to be consistent with the lower-energy data and with five-flavor QCD Monte Carlo prediction and inconsistent with six-flavor production where top quarks are included. We observed five events with thrust < 0.75 in agreement with the five-flavor prediction of 3.5 events and in disagreement with the six-flavor prediction of fifteen events. In conclusion, the independent measurements of R and thrust each rule out open top production with 99% confidence up to $\sqrt{s} = 38.54$ GeV.

An upper limit on the production cross section for a narrow resonance in the data of Figs. 1 and 2 was obtained by fitting the function

$$R = R_0 + R_{\rm res}(B_h \Gamma_{ee}), \qquad (5)$$

where R_0 represents the constant continuum production, $R_{\rm res}(B_h \Gamma_{ee})$ is the function which describes the expected toponium resonance after corrections for machine energy resolution and radiative effects,[10] Γ_{ee} is the width for decay into e^+e^-, and B_h is the hadronic branching ratio. We find that the largest value of $B_h \Gamma_{ee}$ consistent with the data occurs at $\sqrt{s} = 38.343$ GeV and the resulting excitation curve from Eq. (5) is shown in Fig. 2. The corresponding upper limit on the radiatively corrected resonance cross section integrated over energy is 20 ± 8 MeV-nb. Since in lowest order this integrated cross section is

$$\int \sigma_{t\bar{t}}\, d\sqrt{s} = (6\pi^2/M^2) B_h \Gamma_{ee},$$

we obtain a limit on $B_h \Gamma_{ee} < 2.0$ keV at 95% confidence.[11] On the basis of the experimental fact that $\Gamma_{ee}/e_q^{\,2}$ is approximately 10 keV[12] for the vector-meson ground states ρ, ω, φ, J, and Υ and the expectation that B_h is of order 80%,[13] the production of a ground-state vector particle consisting of a $q\bar{q}$ bound state where the quark has charge $\frac{2}{3}e$ should give $B_h \Gamma_{ee}$ of 3.5 keV and is therefore excluded by our scanning data of Figs. 1 and 2.

To study the $\mu^+\mu^- + X$ decay of the b quark we search for events in which both μ^+ and μ^- are in the same hemisphere (forward or backward) as defined by the event thrust axis. We accept events with opening angle between the two muons $> 15°$ and each muon momentum larger than 1.5 GeV. This procedure reduces significantly the background without noticeable reduction in the signal. With this cut our acceptance for the $\mu^+\mu^- + X$ decay of the b quark is 17%. Using a sample of 30 000 hadron events at $\sqrt{s} > 30$ GeV we then expect 1.5 events from background and 18 events from the flavor-changing neutral current if the branching ratio to $\mu^+\mu^- + X$ is 2% as in the models.[6] We find only two events in the data and thus put a 95%-confidence-level upper limit on the $\mu^+\mu^- + X$ decay of B mesons to be less than 0.7%.[14] We conclude that the five-quark model in which bottom is in a weak isospin singlet (or triplet) is ruled out by our data, making it likely that the b quark is in a doublet with the t quark.

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[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); J. E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[2]S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977); Ch. Berger *et al.*, Phys. Lett. 76B, 243 (1978); C. W. Darden *et al.*, Phys. Lett. 76B, 246 (1978).

[3]D. P. Barber *et al.*, Phys. Lett. 108B, 63 (1982).

[4]W. Bartel *et al.*, Phys. Lett. 100B, 364 (1981); Ch. Berger *et al.*, Phys. Lett. 91B, 148 (1980); R. Brandelik *et al.*, Phys. Lett. 113B, 499 (1982); H. J. Behrend *et al.*, DESY Internal Report No. 81-029 (to be published); P. Duinker, Rev. Mod. Phys. 54, 325 (1982).

[5]S. L. Glashow, Phys. Rev. Lett. 45, 1914 (1980); M. Krammer *et al.*, Phys. Lett. 93B, 447 (1980); H. Fritzsch, in Proceedings of the Arctic School of Physics, Akäslompolo, Finland, 1982 (to be published).

[6]H. Georgi and S. Glashow, Nucl. Phys. B167, 173 (1980); G. L. Kane and M. E. Peskin, Nucl. Phys. B195, 29 (1982); H. Georgi and A. Pais, Phys. Rev. D 19, 2746 (1979); J. D. Bjorken and K. Lane, in *Proceedings of the International Neutrino Conference, Baksan, 1977*, edited by M. A. Markov *et al.* (Nauka, Moscow, 1978); F. Gürsey, P. Raymond, and P. Sikivie, Phys. Lett. 60B, 177 (1976); L. L. Chau, "Quark Mixing in Weak Interactions" (to be published).

[7]D. P. Barber *et al.*, Phys. Rep. 63, 337 (1980).

[8]R. P. Feynman and R. D. Field, Nucl. Phys. B136, 1 (1978); A. Ali *et al.*, Nucl. Phys. B167, 454 (1980); A. Ali *et al.*, Phys. Lett. B93, 155 (1980); A. Ali *et al.*,

Nucl. Phys. B168, 409 (1980).
[9]F. A. Berend and R. Kleiss, Nucl. Phys. B178, 141 (1981).
[10]J. D. Jackson and D. L. Scharre, Nucl. Instrum. Methods B128, 13 (1975).
[11]Although we do see a 2.5 standard deviation effect, such an effect is not improbable considering the number of data points in the range of R scanned.
[12]M. Krammer *et al.*, DESY Internal Report No. 80/25, 1982 (unpublished).
[13]J. P. Leveille, University of Michigan Report No. UM-HE-81-11 (to be published).
[14]The preliminary measurement on decay of Υ''' from the Cornell Electron Storage Ring gave a limit of 0.9% at the 90% confidence level (B. Gittelman, private communication).

Spin Analyzing Power in p-p Elastic Scattering at 28 GeV/c

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The analyzing power, A, was measured in proton-proton elastic scattering with use of a polarized proton target and 28-GeV/c primary protons from the alternating-gradient synchrotron. Over the $P_\perp^2$ range of 0.5 to 2.8 (GeV/c)^2, the data show interesting structure. There is a rather sharp dip at $P_\perp^2 = 0.8$ (GeV/c)^2 corresponding to the break in the elastic differential cross section at the end of the diffraction peak.

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Scattering experiments with polarized proton beams and targets allow the study of spin effects in high-energy strong interactions. Any serious theory of strong interactions must now attempt to explain recently discovered unexpected spin effects such as the very large spin-spin forces in high-$P_\perp^2$ proton-proton elastic scattering.[1] We recently studied $p + p \rightarrow p + p$ at 28 GeV and made a high-precision measurement of the analyzing power, A, which is sometimes called the polarization. This one-spin experiment gives information about the spin-orbit interaction in the diffraction scattering region and the medium-$P_\perp^2$ region. We scattered a 28-GeV/c, high-intensity, unpolarized proton beam from our polarized proton target and measured the p-p elastic-scattering cross section in the two possible initial transverse spin states. We detected the elastic-scat-

