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Limits on the production of massive stable charged particles

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We present improved limits on the production of massive stable charged particles in $\bar{p}p$ collisions using the Collider Detector at Fermilab based on an integrated luminosity of 3.54 pb^{-1}. Both unit and fractionally charged particles are considered. Cross-section upper limits are determined for masses from 50 to 500 GeV/c^2. Theoretical cross sections are used to set bounds on the mass of fermionic color triplets, sextets, octets, and decuplets as well as scalar triplets.

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The standard model [1] has enjoyed great success in describing presently known high-energy phenomena. Nevertheless, numerous theories [2,3] have been proposed which go beyond the standard model and predict new phenomena. These theories include left-right-symmetric models, supersymmetry, superstrings, technicolor, chiral color, and composite models [4]. New, hitherto undiscovered particles are a feature common to nearly all of these theories. Massive stable particles (MSPs) are examples. These new particles could belong to one of several different color multiplets and carry fractional or integer charge.

Recently several experiments [5] have reported negative results from searches for MPSs at e^+e^- colliders. However, the sensitivity of these experiments is at present limited to masses less than half the Z^0 mass. In this paper we extend the search for stable particles to higher masses using $\bar{p}p$ collisions at a center-of-mass energy of 1.8 TeV. We consider particles with fractional charges ($Q = \frac{2}{3}$ and $Q = \frac{4}{3}$) as well as unit-charged particles. We consider a particle stable if its lifetime is long enough ($\gamma\tau \gtrsim 10^{-7}$ sec) to enable it to pass through the detector before it decays. We consider the case of pair production of massive stable charged particles via gluon fusion and quark-antiquark annihilation.

The distinguishing characteristics [3,6] of such particles are high transverse momenta, lower velocities than ordinary high-momentum particles, and muonlike penetration of matter. The transverse momenta are characterized by distributions which peak at about one-half of the particles' mass. The velocity distributions are quite broad with centroids that decrease with increasing mass. Although the MSPs are strongly interacting, they can penetrate a considerable amount of material with relatively little loss of energy. Energy loss in coherent electromagnetic or hadronic elastic scattering from the nucleus is negligible because of the small momentum transfer involved [7]. Energy loss in elastic or inelastic

scattering from individual nucleons is small because the MSP is at least 50 times more massive than the nucleon for the range of masses considered here. In particular, the actual amount of energy available in the MSP-nucleon center-of-mass frame is small and lies below the threshold for single-pion production over much of the beta $(\beta=v/c)$ range to which we are sensitive. Charged MSPs, however, do lose energy through ionization which is the prime determinant of their range.

The search is based on an integrated luminosity of 3.54 pb^{-1}, which is a factor of 135 larger than that of our previous search [8].

The Collider Detector at Fermilab (CDF), fully described in Ref. [9], is a general purpose 4π detector with a 1.4-T solenoidal magnetic field. The detector combines electromagnetic and hadronic calorimeters in a projective tower geometry with charged particle tracking. Of particular importance to this analysis are the scintillation counter arrays (beam-beam counters) which signaled the occurrence of an inelastic collision, the vertex time projection chambers (VTPC) which determined the interaction point, the central tracking chamber (CTC), the central hadron calorimeter, and the central muon chambers.

The central hadron calorimeter consists of 32 steel-scintillator layers with 2.5-cm sampling and covers the pseudorapidity range $|\eta|<0.9$. The calorimeter contains projective towers each subtending 0.1 in pseudorapidity and 15° in azimuth (ϕ) where the z axis is along the proton beam direction. Each tower is equipped with a time-to-digital converter (TDC) [10] to record the arrival times of particles from the interaction point. The calorimeter has a timing resolution (σ) of 1.6 ns for noninteracting particles which deposit at least 1.5 GeV of energy in the hadron calorimeter and is nearly 100% efficient for these particles. The mean TDC value for each tower was adjusted using data from jet events so as to equalize the response to presumed $\beta=1$ particles. Event-by-event corrections to the TDC values were made for the interaction time as determined by the beam-beam counters and for the differences in path length arising from different vertex locations along the beam axis.

The central muon chambers consist of four layers of drift cells located immediately behind the hadron calorimeter at a distance of 3.5 m from the beam axis. Over the region $(|\eta| < 0.63)$ covered by the muon chambers, there are approximately five hadronic absorption lengths of material between the chambers and the interaction point.

The acceptance for the detection of stable particles was derived from Monte Carlo studies. ISAJET [11] was used to pair produce stable charged particles. Events were generated at masses ranging from 50 to 500 GeV/c^2. The acceptance for detecting particles with masses less than 50 GeV/c^2 is small and subject to large systematic uncertainties. The cross section for production of particles with masses larger than 500 GeV/c^2 is expected to be extremely small and no events would be anticipated with our present integrated luminosity. Figure 1 shows the β distribution of events generated by ISAJET for three different masses. We are sensitive to a maximum β of about 0.65. The minimum β is determined by the energy
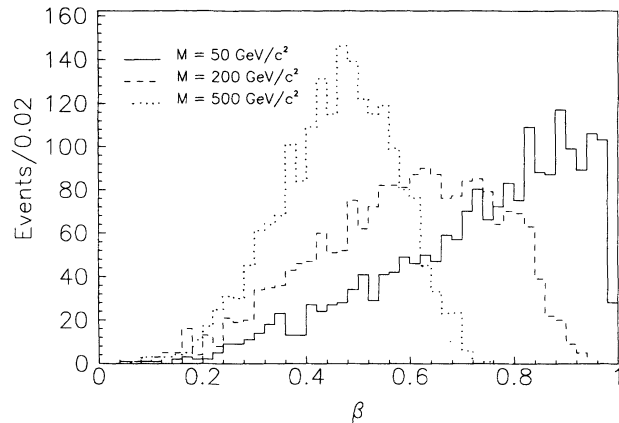

FIG. 1. Monte Carlo–generated β distributions for fermions of mass 50, 200, and 500 GeV/c^2.

required to prevent the particle from stopping due to energy loss in the calorimeter and for $Q=1$ particles varies from 0.25 to 0.45 depending upon the mass of the particle. These events were then processed by a program which simulated the detector response. The same analysis chain used for real data was then applied to the Monte Carlo events. Figure 2 is a scatter plot of the time of arrival relative to $\beta=1$ particles in the hadron calorimeter versus the energy deposited in the hadron calorimeter by unit-charged particles generated with $M=200$ GeV/c^2. The ideal correlation reflecting only the β distribution of the generated particles is indicated by the dashed line. The finite time and energy resolution of the calorimeter result in the scatter around the ideal curve. The signal region for $Q=1$ particles is indicated by the solid lines and was used for all masses. The region of low-time and low-energy deposition was excluded because it is expected to contain significant background from ordinary particles. The area containing 99% of the estimated background lies below the dotted line.
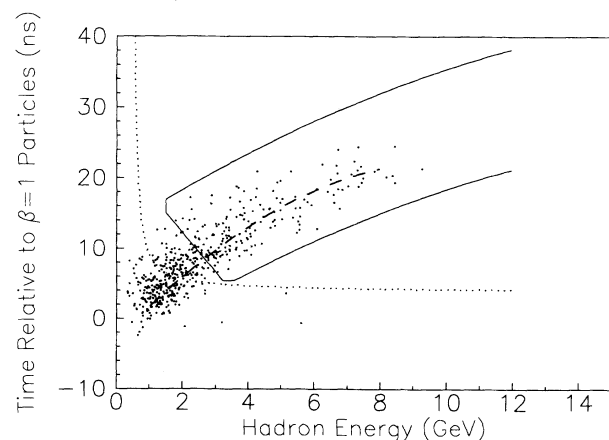

FIG. 2. Time relative to $\beta=1$ particles versus energy deposition in the hadron calorimeter for Monte Carlo generated particles of mass 200 GeV/c^2. The signal region for massive unit-charged stable particles is indicated by the solid lines. The dashed line indicates the response for a detector with perfect resolution. The region encompassing 99% of the background is located below the dotted line.

The acceptance was then defined as the probability of an event having at least one particle with transverse momentum greater than 25 GeV/c in the signal region. The acceptance for unit-charged particles ranged from 5% for 50 GeV/c^2 masses to 40% for masses of 500 GeV/c^2. The increase in acceptance with mass is due to the shift of the β distribution to lower values, the increase in the average transverse momentum (p_T) of the MSP, and the shift in η to more central values. The Monte Carlo studies that were performed for the $Q=1$ case were repeated for $Q=\frac{2}{3}$ and $Q=\frac{4}{3}$. Since the track momenta were reconstructed assuming $Q=1$, the transverse momentum cut of 25 GeV/c becomes an actual p_T cut of 16.7 GeV/c for $Q=\frac{2}{3}$ particles and 33.3 GeV/c for $Q=\frac{4}{3}$ particles. The amount of energy deposition in the calorimeter depends upon the charge of the object, so different signal regions had to be defined for each charge. Charge-$\frac{2}{3}$ particles of a given mass and time-of-flight deposit less energy than similar $Q=1$ particles whereas $Q=\frac{4}{3}$ particles deposit more energy. This leads to different acceptances for the three charges considered.

Because of the penetrating character of MSPs, the data set used in this search consisted of events containing high-p_T muons. The muon trigger required hits in the beam-beam counters indicative of an inelastic collision and a track above 11 GeV/c in the CTC which loosely matched a track segment formed from hits in the muon chambers. The muon trigger efficiency was measured to be 0.90 ± 0.02 [12].

Additional off-line cuts were used to refine the data sample. Events with multiple interactions, as identified by the VTPC, were removed. The vertex position along the beam axis was required to be within 60 cm of the detector center. The penetrating track was required to have $p_T>25$ GeV/c and to match a track segment in the muon chambers to within 10 cm in the drift direction. Cosmic-ray events were removed by requiring the distance of a track from the event vertex along the beam direction to be less than 5 cm and the distance of closest approach to the vertex in the transverse plane to be less than 0.5 cm. The identity of the events tagged as cosmic rays was confirmed by examining the difference in arrival times at the hadron calorimeter between the incoming and outgoing segments comprising each cosmic-ray candidate. This difference as shown in Fig. 3 had a mean value of 20 ns for cosmic ray events and 0 ns for dimuon candidate tracks originating from $\bar{p}p$ interactions. Finally, the hadron calorimeter time was required to be at least 5.4 ns late compared to $\beta=1$ particles. A total of 45 events survived these cuts.

Figure 4 shows the hadron calorimeter time relative to $\beta=1$ particles versus energy deposition for the data sample. The signal regions for $Q=\frac{2}{3}$, $Q=1$, and $Q=\frac{4}{3}$ are indicated. One candidate event (A in Fig. 4) is observed to lie in the signal region for $Q=1$. This event is consistent with $W\rightarrow\mu\nu$ decay based on a high-p_T muon and large missing transverse energy indicative of a neutrino. The late hadron calorimeter time is consistent with background estimates given below. Furthermore, examination of timing information from the outer layers of the
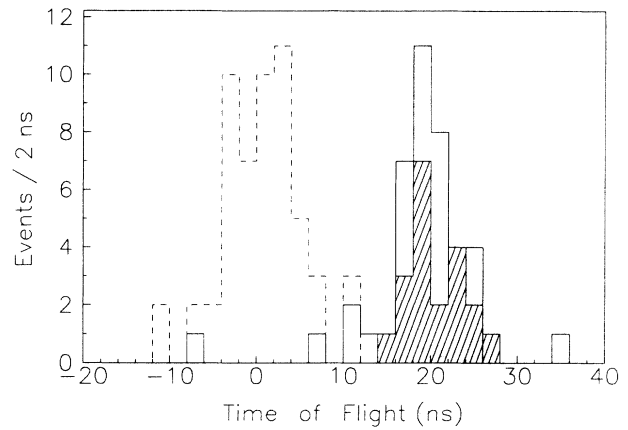

FIG. 3. The calorimeter time difference between pairs of tracks from a sample of $\bar{p}p$ interactions (dashed line) and for a sample of cosmic rays (solid line). The shaded entries indicate events in the data sample used in this analysis which failed the cosmic-ray cuts described in the text and were consequently removed from the sample.

CTC indicates that the track in question is consistent with a $\beta=1$ particle and is unlikely to have as low a velocity as implied by the hadron calorimeter timing. Event B, which lies just outside the signal region, also has CTC timing typical of a $\beta=1$ particle. The signal region for $Q=\frac{2}{3}$ also contains just event A while the signal region for $Q=\frac{4}{3}$ contains event C in addition to A. Event C lies close to the low time boundary of the signal region and therefore is in the region most likely to be populated by tracks in the tail of the time distribution of $\beta=1$ particles. To be conservative, we have elected to retain the two candidate events (A and C) for purposes of setting production limits.

To obtain an estimate of the background, we used a low-p_T ($5<p_T<15$ GeV/c) muon data sample. We applied the same selection criteria to the low-p_T muon sample as the high-p_T muon sample. After normalizing to
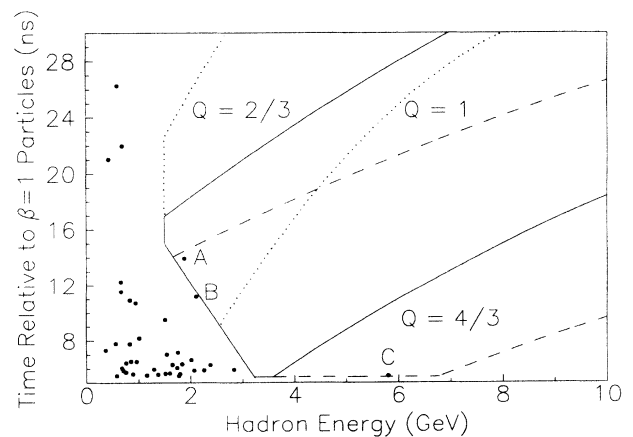

FIG. 4. Time relative to $\beta=1$ particles versus energy deposition in the hadron calorimeter for the high-p_T muon data sample. The signal regions for massive $Q=\frac{2}{3}$, $Q=1$, and $Q=\frac{4}{3}$ stable particles are indicated by the dotted, solid, and dashed lines respectively. Note the suppressed zero.

the number of muon candidates in the two samples, we obtained background estimates of 0.8 ± 0.8 for $Q=\frac{2}{3}$, 2.3 ± 1.3 for $Q=1$, and 1.5 ± 1.1 for $Q=\frac{4}{3}$. These are consistent with the 1, 1, and 2 candidate events found respectively. However, the background content of the low-p_T muon sample may be different from that of the high-p_T muon sample and to be conservative no background subtraction is made.

There are several sources of systematic uncertainty in the determination of the cross-section limits. The uncertainty in the integrated luminosity is $\pm6.8\%$. The major source of systematic error is due to an uncertainty in the response of the calorimeter timing system to particles with different velocities. Data only exist for $\beta=1$ particles. The response to particles with lower β's had to be modeled. The hadron calorimeter has a depth of 130 cm. Because light is collected from the 32 layers and then brought together via light guides at the phototubes, light from any portion of the calorimeter could in principle fire the TDC. Our model indicated that the distance from the event vertex over which the flight time was measured varied from about $\frac{1}{4}$ of the way into the hadron calorimeter for low β particles to about $\frac{3}{4}$ of the way for particles with higher β. The center of the calorimeter was used when determining the acceptance and the change in acceptance resulting from using the $\frac{1}{4}$ and $\frac{3}{4}$ points determined the systematic error assigned to the acceptance. The change in acceptance is dependent upon the β distribution of the particles and therefore varies with mass. The systematic error in the acceptance arising from the uncertainty in the path length ranged from 12% for $M=500$ GeV/c^2 to 38% for $M=50$ GeV/c^2.

Another potential cause of loss of acceptance is due to overlapping tracks. Because a TDC fires on the first signal that reaches it, it is possible for a $\beta=1$ particle hitting the same calorimeter tower as a slower particle to result in a loss of timing information. The overlapping track could originate from either the underlying event or from the fragmentation of a parent exotic quark. The probability of a particle from the underlying event striking the same tower as the MSP was estimated to be 0.0046 ± 0.0016. Although model dependent, particles accompanying the MSP are generally expected to have low momenta [13] and be swept away from the high-momentum massive particle by the 1.4-T magnetic field. Monte Carlo simulations utilizing ISAJET confirmed this expectation. We conclude that the effect of overlapping particles is small and make no correction.

The total systematic uncertainty ranged from 39% for $M=50$ GeV/c^2 to 15% for $M=500$ GeV/c^2. The 95% confidence level upper limit on the cross section was then determined by convoluting the Poisson statistics associated with the number of observed events together with the systematic uncertainty, and correcting for the acceptance. Figure 5 gives the resulting 95% confidence level upper cross-section limits on the production of stable charged colored particles. Although these limits were calculated for the case of fermionic colored objects, the limits are valid for any particles pair produced with the same kinematic distributions and pattern of energy deposition and thereby the same acceptance. Also shown are
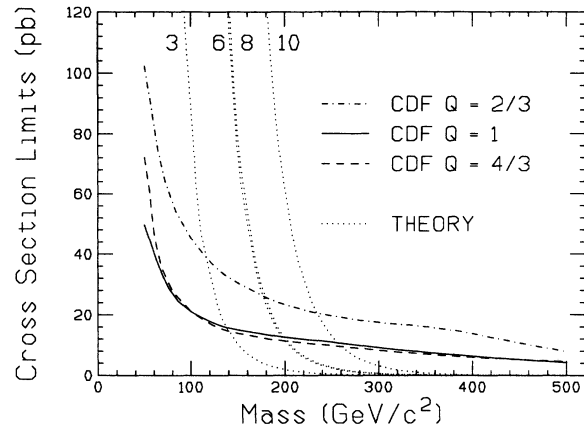

FIG. 5. The cross section upper limits (95% C.L.) for the pair production of stable charged fermionic colored particles as a function of mass for $Q=1$, $Q=\frac{2}{3}$, and $Q=\frac{4}{3}$. Also shown are the theoretical cross sections for the production of fermionic color triplets (3), sextets (6), octets (8), and decuplets (10).

theoretical cross sections [14] for the production of fermionic color triplets, sextets, octets, and decuplets.

Knowledge of theoretical cross sections allows one to set limits on the masses of particles produced with those cross sections. The Ellis cross sections for the case $\Lambda_5=170$ MeV, $\mu=m$, and Diemoz-Ferroni-Longo-Martinelli (DFLM) [15] structure functions rule out stable, pair produced, fermionic unit-charged color triplets with masses between 50 and 139 GeV/c^2 at the 95% confidence level. Using the same cross sections, charge-$\frac{2}{3}$ objects produced with masses between 50 and 116 GeV/c^2 are excluded as are charge-$\frac{4}{3}$ objects with masses between 50 and 140 GeV/c^2 at the 95% confidence level. The charge refers to that of the detected particle and not necessarily to that of the original quark which could form a bound state with a light quark.

Mass limits can also be set for higher color multiplets by scaling the same Ellis color-triplet cross sections by the appropriate color factors taking into account the change in the ratio of the cross sections with mass [16]. Unit-charged color sextets, octets, and decuplets are excluded at the 95% confidence level for masses between 50 GeV/c^2 and 197, 199, and 255 GeV/c^2 respectively. In addition unit-charged scalar triplets with masses between 50 and 85 GeV/c^2 are excluded at the 95% confidence level using the cross sections of Drees and Tata [6].

All these limits are based upon the assumption that the massive particles have nonzero charge. Obviously pair production could involve neutral as well as charged particles. In addition, interactions with the material of the detector could change the original charge of the massive particles. These effects could weaken the cross section limits by a factor between 1.5 and 4.0 [6]. A factor of 4 would lower the mass limits by 30–40 GeV/c^2. Although massive leptons if present could have been detected, the expected cross section for their production is much smaller than the corresponding cross section for the production of colored particles of the same mass. Therefore we do not set limits on the production of massive stable leptons.

[1] S. L. Glashow, Nucl. Phys. **22**, 579 (1961); S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksel, Stockholm, Sweden, 1968), p. 367; S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970); M. Kobayashi and M. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] E. Eichten *et al.*, Rev. Mod. Phys. **56**, 579 (1984), and references quoted therein.

[3] S. Errede and S.-H. Henry Tye, in *Proceedings of the 1984 Summer Study on the Design and Utilization of the SSC*, Snowmass, Colorado, 1984, edited by J. Morfin and R. Donaldson (Division of Particles and Fields of the American Physical Society, New York, 1984), p. 175, and references quoted therein.

[4] J. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); Phys. Lett. **58B**, 333 (1975); R. E. Marshak and R. N. Mohapatra, *ibid.* **91B**, 222 (1980); K. Enqvist, K. Mursula, and M. Roos, Nucl. Phys. **B207**, 233 (1982); **B226**, 121 (1983); M. Roos, Phys. Lett. **135B**, 487 (1984); J. Wess and B. Zumino, Nucl. Phys. **B70**, 39 (1974); H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. E. Haber and G. L. Kane, *ibid.* **117**, 75 (1985); J. H. Schwarz, Phys. Rep. **89**, 223 (1982); M. Green and J. Schwarz, Phys. Lett. **149B**, 117 (1984); F. Wilczek and A. Zee, Phys. Rev. D **16**, 860 (1977); Harald Fritzsch, Phys. Lett. **78B**, 611 (1978); W. J. Marciano, Phys. Rev. D **21**, 2425 (1980); Michael E. Peskin, in *Lepton and Photon Interactions at High Energies*, Proceedings of the 10th International Symposium, Bonn, Germany, 1981, edited by W. Pfeil (Physikalisches Institut, University of Bonn, Bonn, 1981), p. 880; M. Abolins *et al.*, in *Elementary Particle Physics and Future Facilities*, Proceedings of the 1982 DPF Summer Study, Snowmass, Colorado, 1982, edited by R. Donaldson, R. Gustafson, and F. Paige (Division of Particles and Fields of the APS, New York, 1983), p. 274; P. Fishbane, S. Meshkov, and P. Ramond, Phys. Lett. **134B**, 81 (1984); C. Wetterich, *ibid.* **167B**, 325 (1986); P. H. Frampton and S. L. Glashow, Phys. Lett. B **190**, 157 (1987); T. Banks and M. Karliner, Nucl. Phys. **B281**, 399 (1987); E. Narki and E. Roulet, Phys. Lett. B **245**, 105 (1990).

[5] I. Adachi *et al.*, Phys. Lett. B **249**, 336 (1990); P. Abreu *et al.*, *ibid.* **247**, 157 (1990); M. Z. Akrawy *et al.*, *ibid.* **252**, 290 (1990); D. Decamp *et al.*, *ibid.* **236**, 511 (1990); E. Soderstrom *et al.*, Phys. Rev. Lett. **64**, 2980 (1990); K. Abe *et al.*, *ibid.* **61**, 915 (1988); G. N. Kim *et al.*, Int. J. Mod. Phys. A **6**, 2583 (1991).

[6] M. Drees and X. Tata, Phys. Lett. B **252**, 695 (1990); and (private communication).

[7] A. Schiz *et al.*, Phys. Rev. D **21**, 3010 (1980).

[8] F. Abe *et al.*, Phys. Rev. Lett. **63**, 1447 (1989).

[9] F. Abe *et al.*, Nucl. Instrum. Methods A **271**, 387 (1988).

[10] G. Drake *et al.*, Nucl. Instrum. Methods A **269**, 68 (1988).

[11] F. E. Paige and S. D. Protopopescu, ISAJET Version 6.22, BNL Report No. 38034, 1986 (unpublished).

[12] F. Abe *et al.*, Phys. Rev. D **43**, 2070 (1991).

[13] G. Ingelman and C. Wetterich, Phys. Lett. B **174**, 109 (1986).

[14] R. K. Ellis, Fermilab Report No. FERMILAB-Pub-91/30-T, 1991 (unpublished); and (private communication).

[15] M. Diemoz, F. Ferroni, E. Longo, and G. Martinelli, Z. Phys. C **39**, 21 (1988); J. V. Allaby *et al.*, Phys. Lett. B **197**, 281 (1987).

[16] H. Tanaka and I. Watanabe, Int. J. Mod. Phys. A **7**, 2679 (1992).