# Search for Light Supersymmetric Baryons

I. F. Albuquerque,[6,*] N. F. Bondar,[3] R. Carrigan, Jr.,[1] D. Chen,[10,†] P. S. Cooper,[1] Dai Lisheng,[2] A. S. Denisov,[3] A. V. Dobrovolsky,[3] T. Dubbs,[5,‡] A. M. F. Endler,[8] C. O. Escobar,[6] M. Foucher,[7,§] V. L. Golovtsov,[3] H. Gottschalk,[1,‖] P. Gouffon,[6,¶] V. T. Grachev,[3] A. V. Khanzadeev,[3] M. A. Kubantsev,[4,**] N. P. Kuropatkin,[3] J. Lach,[1] J. Langland,[5] Lang Pengfei,[2] Li Chengze,[2] Li Yunshan,[2] M. Luksys,[13] J. R. P. Mahon,[6,¶,††] E. McCliment,[5] A. Morelos,[1,‡‡] C. Newsom,[5] M. C. Pommot Maia,[9] V. M. Samsonov,[3] V. A. Schegelsky,[3] Shi Huanzhang,[2] V. J. Smith,[11] Tang Fukun,[2] N. K. Terentyev,[3] S. Timm,[12,§§] I. I. Tkatch,[3] L. N. Uvarov,[3] A. A. Vorobyov,[3] Yan Jie,[2] Zhao Wenheng,[2] Zheng Shuchen,[2] and Zhong Yuanyuan[2]

(E761 Collaboration)

[1]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[2]*Institute of High Energy Physics, Beijing, People's Republic of China*

[3]*St. Petersburg Nuclear Physics Institute, Gatchina, Russia*

[4]*Institute of Theoretical and Experimental Physics, Moscow, Russia*

[5]*University of Iowa, Iowa City, Iowa 52242*

[6]*Universidade de Sao Paulo, Sao Paulo, Brazil*

[7]*J. W. Gibbs Laboratory, Yale University, New Haven, Connecticut 06511*

[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*

[9]*Conselho Nacional de Pesquisas CNPq, Rio de Janeiro, Brazil*

[10]*State University of New York at Albany, Albany, New York 12222*

[11]*H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*

[12]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*

[13]*Universidade Federal da Paraiba, Paraiba, Brazil*

(Received 28 February 1996; revised manuscript received 28 January 1997)

We have searched for the production and decay of light supersymmetric baryons produced in 800 GeV/$c$ proton copper interactions in a charged hyperon beam experiment. We observe no evidence for the decays $R^+(uud\tilde{g}) \rightarrow S^0(uds\tilde{g})\pi^+$ and $X^-(ssd\tilde{g}) \rightarrow S^0(uds\tilde{g})\pi^-$ in the parent mass and lifetime ranges of 1700–2500 MeV/$c^2$ and 50–500 ps. Production upper limits for $R^+$ at $x_F = 0.47$, $P_t = 1.4$ GeV/$c^2$ and $X^-$ at $x_F = 0.48$, $P_t = 0.65$ GeV/$c^2$ of less than $10^{-3}$ of all charged secondary particles produced are obtained for all but the highest masses and shortest lifetimes predicted. [S0031-9007(97)03037-8]

PACS numbers: 13.85.Rm, 14.80.Ly

Recent theoretical work [1–3] has proposed a supersymmetric model with a light gluino [$\tilde{g}$] in the mass range 100–600 MeV/$c^2$. A direct consequence of this model is the prediction of a set of supersymmetric hadrons in the 1000–3000 MeV/$c^2$ mass range. We have searched for two weak decay modes between these hadrons in an attempt to either confirm this hypothesis or close the low mass window for supersymmetry.

Among the light hadrons predicted [1–3] are the supersymmetric partners of the proton $R^+(uud\tilde{g})$; $\Xi^-$, $X^-(ssd\tilde{g})$; as well as the $S^0(uds\tilde{g})$. Characteristically, the predicted mass and lifetime ranges for those states which have weak decays are 1700–2500 MeV/$c^2$ and 50–500 ps. The mass splitting predicted [3] between the $R^+$ and $S^0$ is $\Delta M_{\rm RS} = M_{R^+} - M_{S^0} = 210 \pm 20$ MeV/$c^2$. The $S^0$ is less massive than the $R^+$ in this model [3] due to the very strong attraction of the flavor singlet quarks in the $S^0$. In this model this state is the lowest mass superbaryon. Only strangeness changing weak decays are allowed between the lowest mass superbaryons, unless the mass splittings are large enough to allow strong decay by kaon emission. If the mass splittings are similar to the hyperon system, as expected for the $R^+$-$S^0$ system, the lifetimes and decay modes of the superbaryons should mimic the hyperons. Limits on the production rate of $R^+$ and $X^-$ as a function of mass and lifetime can be set in charged hyperon beam searches. We report such a search. We have not assumed the predicted mass splitting; we perform the search as a function of this parameter. For $\Delta M_{\rm RS}$ less than $M_\pi$ the $R^+$ decay is forbidden. For $M_\pi < \Delta M_{\rm XS} < M_K$ the $X^-$ is stable against strong decay via kaon emission and weak decay via pion emission is allowed. We assume the dominant decays are $R^+ \rightarrow S^0\pi^+$ and $X^- \rightarrow S^0\pi^-$ analogous to the normal hyperon decays $\Sigma^+ \rightarrow n\pi^+$ and $\Xi^- \rightarrow \Lambda^0\pi^-$.

Fermilab experiment E761 was a high statistics study of hyperon radiative decays. We reconstructed [4] $48 \times 10^6$ $\Sigma^+ \rightarrow p\pi^0$ and $38 \times 10^3$ $\Sigma^+ \rightarrow p\gamma$ decays from data taken in 1990. Unfortunately, this data set cannot be used for an $R^+$ search, since the trigger required a photon in the final state. In our observation of the $\Xi^- \rightarrow \Sigma^-\gamma$ decay [5] we took negative beam data in a different configuration of the apparatus. This had good acceptance for low momentum charged secondaries but also required a photon trigger. In order to control the photon trigger rate for these negative beam data we added a scintillator positioned to veto the pions from the $\Sigma^- \to n\pi^-$ mode. Subsequently, we removed the photon spectrometer from the apparatus and took data requiring only a beam particle and a signal in the pion veto scintillator as a trigger in order to measure the yields [6] and production polarizations [7] of the negative hyperons using their hadronic decay modes. These data permitted a search for $X^- \to S^0\pi^-$. As part of this study we briefly returned to positive beam running with the same trigger. These data are available to search for $R^+ \to S^0\pi^+$. Together these data comprise $\sim$1% of the data taken by E761.

The trigger required only an incoming charged parent particle and a charged daughter with less than 40% of the incoming parent's momentum. The daughter is assumed to be a $\pi^\pm$. The neutral daughter is assigned the mass of the $S^0$. Using momentum conservation to measure the momentum of the unseen neutral daughter, we reconstruct the mass of the parent. We search for a bump in the mass spectrum of the reconstructed parent particle as a function of the assumed $S^0$ mass. After corrections for acceptance and decay losses, we can determine upper limits on the fraction of $R^+$ and $X^-$ produced within our hyperon beam's acceptance as a function of the assumed parent mass and lifetime. In the following text the parameters for the positive (negative) beam samples [$R^+(X^-)$ decays] are shown as in this sentence.

The E761 charged hyperon beam was located in the Proton Center beam line at Fermilab. 800 GeV/$c$ protons interacted in a $0.5 \times 2.0$ mm$^2$ $\times$ 150 mm long copper target. A magnet and beam channel downstream of the target selected positive (negative) secondaries with $\langle P \rangle = 378$ (382) GeV/$c$ at a production angle near 3.7 (1.7) mrad. The production variables of the hyperon beam were $x_F = 0.47$ (0.48), $P_t = 1.4$ (0.65) GeV/$c$ with acceptances (FWHM) in these quantities of $\Delta x_F = 0.04$ and $\Delta P_t = 0.4$ GeV/$c$. $5.9(1.8) \times 10^{13}$ protons were incident on the production target for these data. About half of these interacted in the target. $173(169) \times 10^6$ secondaries were observed at the channel exit of the hyperon beam. The larger secondary yield in the negative beam was due to the smaller production $P_t$. $3.45(4.55) \times 10^6$ triggers were recorded with a live time of 47(35)%.

The standard E761 analysis and cuts are applied to these data [4–6]. Events are selected which have well reconstructed parent and daughter charged tracks with at least a 100 $\mu$rad decay angle $[\theta]$ between them, a vertex position in a 12 m long decay region beginning 13.6 m from the hyperon production target and a daughter to parent momentum ratio $r < 0.4$. The details of the beam, apparatus and analysis are described elsewhere [4–7].

Figure 1 shows a $\theta$-$r$ scatter plot of the positive data. Superimposed are the two body kinematics curves for the known hyperon decays in this region and a set of curves for the decay $R^+ \to S^0\pi^+$ parametric in the $S^0$ mass and assuming the predicted value for $\Delta M_{\mathrm{RS}}$. A large $\Sigma^+ \to n\pi^+$ component ($112 \times 10^3$ events) is clearly seen. The acceptance of the trigger drops rapidly below

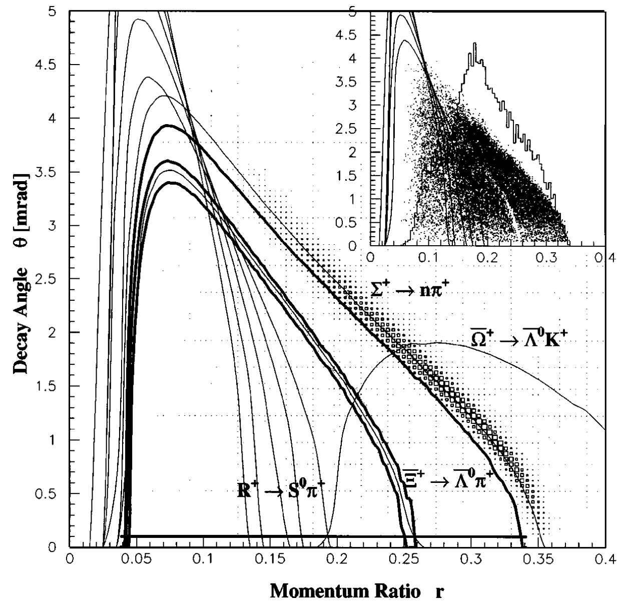


FIG. 1. $\theta$-$r$ box plot (box area proportional to events/cell) for the positive event sample. The solid curves shown are the expected locations of two body decay modes of 378 GeV/$c$ parents in these variables. The modes shown are (from right to left) $\overline{\Omega}^+ \to \overline{\Lambda}^0 K^+$, $\Sigma^+ \to n\pi^+$, $\overline{\Xi}^+ \to \overline{\Lambda}^0\pi^+$, $R^+ \to S^0\pi^+$ with $M_{S^0} = 1500$, 1700, 1900, 2100, 2300 MeV/$c^2$; $\Delta M_{\mathrm{RS}} = 210$ MeV/$c^2$. The heavy curves show the cuts for the $R^+$ search. The inset shows a scatter plot for the same distribution after the cuts have been imposed (14 127 events). The histogram displays the $r$ distribution for these events.

$r = 0.15$ ($P_{\pi^+} \sim 50$ GeV/$c$) due to low momentum daughter tracks missing the trigger counter. Events remain at lower momenta due to interactions which fire the trigger counter even when the daughter misses. The events not associated with two body decays are dominated by interactions and constitute the background to this search. Our acceptance to the $R^+ \to S^0\pi^+$ decay is in the $\theta$-$r$ region, $\theta < 3$ mrad, $0.15 < r < 0.20$.

In order to illustrate the sensitivity of our apparatus to two body decays we show $\Sigma^+ \to n\pi^+$ and $\overline{\Xi}^+ \to \overline{\Lambda}^0\pi^+$ events in these data. The results are shown as reconstructed parent mass plots in Fig. 2. In addition to the $\Sigma^+$ events [Fig. 2(a)], which were already obvious on the $\theta$-$r$ plot, we observe $1221 \pm 59$ $\overline{\Xi}^+$ events [Fig. 2(b) full curve] with a mass resolution $[\sigma]$ of 1.9 MeV/$c^2$ Since the predictions of the model do not tell us the mass of either parent or daughter superbaryon we must be concerned with the dependence of our parent mass resolution on an incorrect daughter mass assumption. We test this using the $\overline{\Xi}^+$ events. The dashed curve and fit in Fig. 2(b) are the same events analyzed using $M_{\Lambda^0}$ shifted 50 MeV/$c^2$ above the accepted value. The $\overline{\Xi}^+$ peak shifts as expected and the peak width increases from 1.9 to 2.7 MeV/$c^2$. This peak shifts $<$8 MeV/$c^2$ in the mass difference of the reconstructed parent and the assumed neutral daughter mass ($\Delta M$).

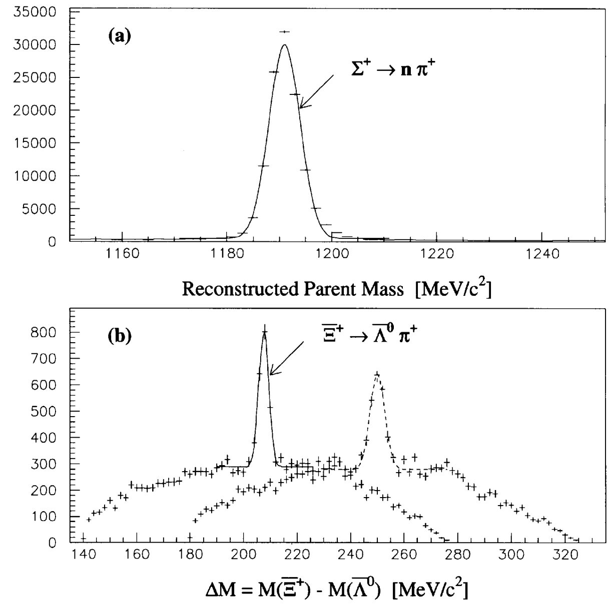


FIG. 2. Reconstructed parent mass plots for the known hyperon decays in the data sample. The fits shown are Gaussian plus linear backgrounds. (a) The $\Sigma^+ \to n\pi^+$ sample. (b) The $\overline{\Xi}^+ \to \overline{\Lambda}^0\pi^+$ sample. The abscissa is the reconstructed parent mass minus the $\Lambda^0$ mass. The dashed curve and fit are the same events analyzed with an assumed $\Lambda^0$ mass shifted 50 MeV$/c^2$ above the accepted value.

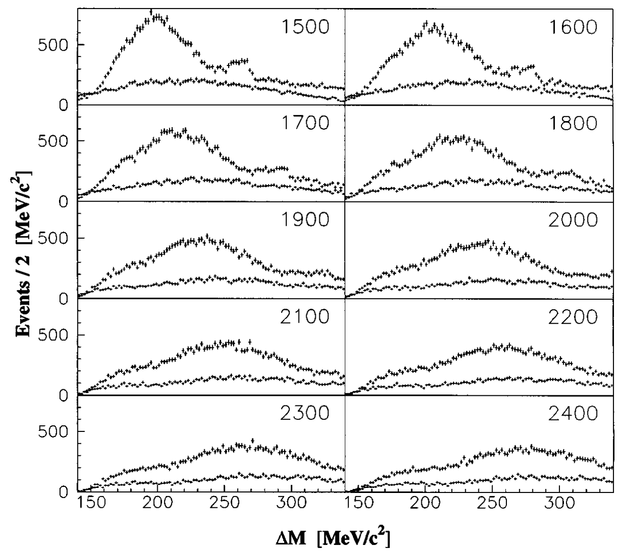


FIG. 3. $R^+$ and $X^-$ mass plots for assumed $D^0$ masses from 1500–2400 MeV$/c^2$ as a function of $\Delta M$, the $R^+(X^-), S^0$ mass difference. The $X^-$ data are the upper curves on each plot. The feature near $\Delta M = 250$–$275$ MeV$/c^2$ in the $X^-$ data at low $S^0$ mass reflects the removal of $\Xi^- \to \Lambda^0\pi^-$ events.

To search for the $R^+(X^-) \to S^0\pi^{+(-)}$ decay modes we plot the reconstructed parent mass minus assumed $S^0$ mass, $\Delta M$, for 10 different values of the $S^0$ mass spaced by 100 MeV$/c^2$ in Fig. 3. The $S^0$ would be reconstructed within 50 MeV$/c^2$ of its actual mass on one of these plots. These events are selected to have a reconstructed $\Sigma^{+(-)}$ mass below the $\Sigma^{+(-)} \to n\pi^{+(-)}$ mass band $[M(\Sigma^{+(-)}) < 1179\ (1185)\ \text{MeV}/c^2]$, to be inconsistent with the $\Xi^{+(-)} \to \Lambda^0\pi^{+(-)}$ hypothesis ($|M(\Xi) - 1321| < 3\ (6)$ MeV$/c^2$), and to have a decay angle greater than 100 $\mu$rad. These cuts are shown as the heavy curves on Fig. 1. This sample of 14 127 positive events is shown in the inset of Fig. 1. The negative sample (not shown) contains 34 345 events. The plots of Figs. 2 and 3 are in 2 MeV$/c^2$ mass bins, which is the typical peak width $[\sigma]$ we expect for any signal. Any single bin effect is too narrow to be consistent with our resolution and, therefore, must be a statistical fluctuation. There are 2000 data points displayed in Fig. 3, where both positive and negative data are shown on each plot. The number of $>3\sigma$ single bin fluctuations is consistent with expectations. The peaks in Fig. 2(b) demonstrate how a ~1000 event signal would appear in our apparatus.

We measure the fraction of all charged particles produced in the acceptance of the secondary beam which are of a particular particle type. To quantify upper limits to the production fraction of $R^+(X^-)$ we choose the predicted $R^+(X^-)$ $S^0$ mass difference to be $\Delta M = 210$ MeV$/c^2$ and fit a Gaussian mass resolution function with mean fixed at $\Delta M$ and width $[\sigma]$ fixed at 2 MeV$/c^2$. The 90% CL upper limit to the amplitude of the Gaussian fit is twice the statistical error $[\Delta N \sim 25\ (50)$ events$]$. We ignore the statistical fluctuations in the particular few bins near $\Delta M = 210$ MeV$/c^2$ in each mass plot. We evaluate upper limits as a function of lifetime for the five left mass plots in Fig. 3. Similar upper limits would apply to different values of the mass splitting $\Delta M$. The upper limit scales as the square root of the number of events at the corresponding value of $\Delta M$.

We use a simple Monte Carlo apparatus simulation to determine the mass resolution and acceptance for these decays. It reproduces the mass resolutions obtained from the known hyperon decays. The mass resolution for $R^+$ decays is 1.65 MeV$/c^2$ independent of $R^+$ mass, nearly the same value as observed for $\overline{\Xi}^+$ decays. This simulation does not take interactions into account and cannot reproduce the triggers below $r = 0.15$. Given that we have no information on the interaction properties of superbaryons this is the safe course in determining an upper limit to production. After correction for branching ratios and the fraction of produced parents which decay in the decay region [the decay factor; $D(\tau)$] the fraction of particles of each type at production are shown in Table I. The acceptances and decay factors are determined at the accepted lifetime [8] of the $\Sigma^+$. The $R^+(X^-)$ branching ratio is assumed to be unity. These upper limits are shown as a function of the $R^+(X^-)$ mass and lifetime in Fig. 4. The lifetime dependence of the upper limit is given by the decay factor; $\text{UL}(\tau) = \text{UL}(\tau_{\Sigma^+})D(\tau_{\Sigma^+})/D(\tau)$ with

$$D(\tau) = \exp[-L_p/(c\tau P/M)] \times \{1 - \exp[-L_d/(c\tau P/M)]\},$$

TABLE I. Decay mode production fractions.

| Mode | Acceptance | Events [<90% CL] | Decay factor | Production fraction |
|---|---|---|---|---|
| $\Sigma^+ \to n\pi^+$ | 41% | 112 200 | 0.134 | $5 \times 10^{-2}$ |
| $\overline{\Xi}^+ \to \Lambda^0\pi^+$ | 38% | 1221 | 0.219 | $1.7 \times 10^{-4}$ |
| $R^+[1710] \to S^0[1500]\pi^+$ | 20% | <62 | 0.070 | $<5.1 \times 10^{-5}$ |
| $R^+[1910] \to S^0[1700]\pi^+$ | 13% | <53 | 0.054 | $<9.1 \times 10^{-5}$ |
| $R^+[2110] \to S^0[1900]\pi^+$ | 4.0% | <47 | 0.041 | $<3.4 \times 10^{-4}$ |
| $R^+[2310] \to S^0[2100]\pi^+$ | 0.43% | <45 | 0.031 | $<4.0 \times 10^{-3}$ |
| $R^+[2510] \to S^0[2300]\pi^+$ | $1 \times 10^{-6}$ | <35 | 0.029 | $<7.3 \times 10^{-1}$ |
| $\Sigma^- \to n\pi^-$ | 41% | 805 770 | 0.220 | $2.5 \times 10^{-1}$ |
| $\Xi^- \to \Lambda^0\pi^-$ | 38% | 81 946 | 0.219 | $1.4 \times 10^{-2}$ |
| $\Omega^- \to \Lambda^0 K^-$ | 44% | 889 | 0.079 | $5.2 \times 10^{-4}$ |
| $X^-[1710] \to S^0[1500]\pi^-$ | 20% | <114 | 0.072 | $<1.1 \times 10^{-4}$ |
| $X^-[1910] \to S^0[1700]\pi^-$ | 13% | <108 | 0.055 | $<2.1 \times 10^{-4}$ |
| $X^-[2110] \to S^0[1900]\pi^-$ | 4.0% | <94 | 0.042 | $<7.7 \times 10^{-4}$ |
| $X^-[2310] \to S^0[2100]\pi^-$ | 0.43% | <78 | 0.032 | $<7.9 \times 10^{-3}$ |
| $X^-[2510] \to S^0[2300]\pi^-$ | $1 \times 10^{-6}$ | <66 | 0.024 | $<3.7 \times 10^{-1}$ |

where $L_p$ is the distance from production to the start of the decay region (13.6 m), $L_d$ is the length of the decay region (12.0 m), $P$ is the average parent momentum [378 (382) GeV$/c$], $M$ is the parent mass, and $\tau$ is the parent lifetime.

The total production cross section in 800 GeV$/c^2$ $pN$ interactions for $>3$ GeV$/c^2$ gluinos has been calculated by Dawson, Eichten, and Quigg [9]. We extrapolate this calculation to the 100–600 MeV$/c^2$ gluino mass range and assume that gluinos hadronize into baryons 10% of the time in analogy with the strange quark. The resulting production cross section for superbaryons is in the range 30–80 $\mu$b or $(1\text{–}3) \times 10^{-3}$ of the inelastic cross section. The extrapolation of this perturbative QCD calculation to such low masses is unreliable. Absent better theoretical predictions, this estimate provides an order of magnitude for the superbaryon production fraction.

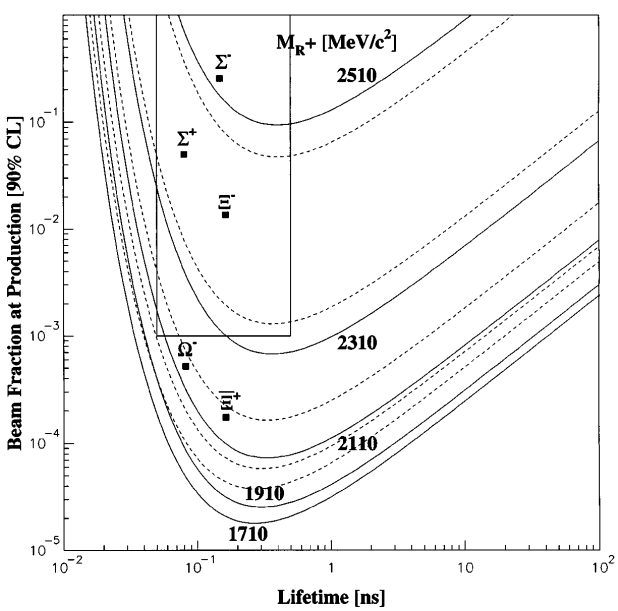


FIG. 4. Production fraction 90% CL upper limits for $R^+$ (solid) and $X^-$ (dashed) as a function of parent mass and lifetime. Our observed hyperon production fractions are also shown. The box shown is the predicted lifetime range and our estimate of $10^{-3}$ for the scale at which such particles might be produced.

Qualitatively, if the gluino is as light as the $s$ quark (current quark mass $\sim$150 MeV$/c^2$) then it should be no more difficult to produce an $R^+$ than a $\Sigma^+$ hyperon. We clearly rule this case out. Charmed hadrons are produced with production fractions in the $10^{-3}$–$10^{-4}$ range. Since the charmed quark ($\sim$1500 MeV$/c^2$) is 2.5 times heavier than the heaviest gluino allowed by the model [1–3], one would expect to observe $R^+$ and $X^-$ production with beam fractions above $10^{-3}$. We rule this out for all but the highest mass and shortest lifetime superbaryons allowed by the model.

Neither of these production fraction estimates is a calculation of the superbaryon production cross section. They do indicate a level ($\sim 10^{-3}$) at which upper limits become meaningful in constraining models of this type. We observe no evidence for the production and subsequent pionic decay of superbaryons with upper limits below $10^{-3}$ of the total cross section over much of the allowed parameter space of this model.

We acknowledge Tom Devlin and Glennys Farrar for first bringing this problem to our attention and helpful conversations with several of our Fermilab colleagues: Jeff Appel, Estia Eichten, and Chris Quigg. We wish to thank the staffs of Fermilab and the Petersburg Nuclear Physics Institute for their assistance. This work is supported in part by the U.S. Department of Energy under Contracts No. DE-AC02-76CH03000, No. DE-AC02-76ER03075, No. DE-FG02-91ER40631, No. DE-FG02-91ER40664, and No. DE-FG02-91ER40682, the Russian Academy of Sciences, and the UK Science and Engineering Research Council.

*Supported by FAPESP, Brazil. Now at Rutgers University, Piscataway, NJ.
†Now At Fermilab, Batavia, IL 60510.
‡Present address: Department of Physics, University of California (Santa Cruz), Santa Cruz, CA 95046.
§Present address: Department of Physics, University of Maryland, College Park, MD 20742.
‖Present address: COPPE, Universidade Federal do Rio de Janeiro, Brazil.
¶Partially supported by FAPESP and CNPq, Brazil.
**Partially supported by the International Science Foundation.
††Now at the Universidade Estadual do Rio de Janeiro, Brazil.
‡‡Partially supported by CONACyT, México. Present address: Instituto de Física, University Autónoma de San Luis Potosí, San Luis Potosí, S.L.P. 78240 México.
§§Present address: Department of Physics, SUNY Albany, Albany, NY 12222.

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