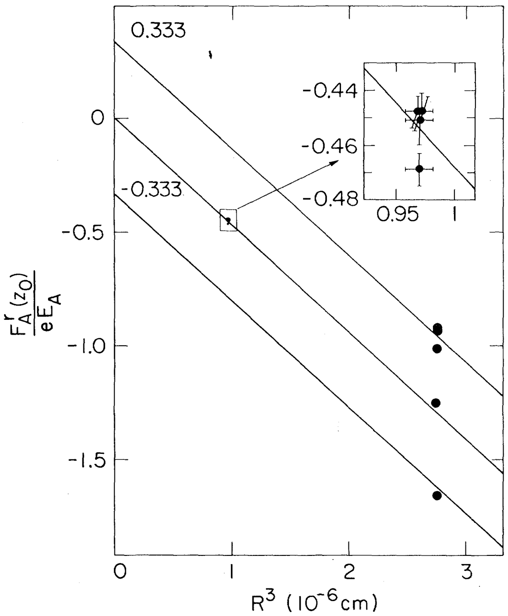

FIG. 6. $F_A{}^r/eE_A$ at z_0 vs R^3 for set 2 of cooldown 1. The statistical errors are the size of the points unless otherwise indicated.

conclude that residual charge of $\frac{1}{3}e$ exists on niobium spheres. We are continuing with the experiment and are preparing a detailed paper.

This work was supported by National Science Foundation Grant No. PHY-79-00024.

[1]G. S. LaRue, Ph.D. thesis, Stanford University, 1978 (unpublished).

[2]G. S. LaRue, W. M. Fairbank, and A. F. Hebard, Phys. Rev. Lett. 38, 1011 (1977).

[3]G. S. LaRue, W. M. Fairbank, and J. D. Phillips, Phys. Rev. Lett. 42, 142, 1019(E) (1979).

[4]G. S. LaRue, J. D. Phillips, and W. M. Fairbank, in Proceedings of the Twentieth International Conference on High Energy Physics, Madison, Wisconsin, July 1980 (to be published).

[5]The values of χ^2 per degree of freedom for the three groups are, respectively, 1.3, 0.9, and 1.2.

[6]M. Marinelli and G. Morpurgo, Phys. Lett. 94B, 427, 433 (1980), have reported a charge-mimicking effect which they attributed to a new magnetoelectric effect. M. Buckingham and C. Herring, Phys. Lett. 98B, 461 (1981), have shown that this can be accounted for by a tilting of the mean magnetic moment, even for a spinning ball. M. Marinelli and G. Morpurgo, to be published, agree. They report zero fractional charges on 3.7 mg of steel. In our experiment, because the electric and magnetic fields are parallel, this effect is < 0.01 e (see Refs. 1–4).

Search for Baryon-Exchange Production of Strange Exotic Mesons

R. M. Bionta,[a] A. S. Carroll, R. M. Edelstein, D. R. Green, E. J. Makuchowski,[b] S. P. Morrissey, J. S. Russ, J. J. Russell, N. Sharfman,[c] and R. B. Sutton
Brookhaven National Laboratory, Upton, New York 11973, and Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213, and Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 22 December 1980)

Results are presented of a search for strange, doubly charged, narrow [full width at half maximum ≤ 0.2 (GeV/c^2)^2] meson states produced in the baryon-exchange reaction $\pi^+p \to \Lambda_f{}^0S^{++}$ at 9.8 GeV/c. No evidence is found for such states. The 95%-confidence-level limit for the production cross section is < 20 nb for $M(S^{++}) \leq 2$ GeV/c^2. Limits on σB from a kinematic reconstruction of final states with $S^{++} \to K^+\pi^+$ are ≤ 10 nb for $M(K^+\pi^+) \leq 2.0$ GeV/c^2.

PACS numbers: 14.40.Pe, 13.75.Gx

Multiquark exotic mesons are expected in many models of hadrons[1] having quantum numbers in excess of the values available to simple $\bar{q}q$ systems. In contrast to these models, perturbative quantum-chromodynamic analysis based on single-gluon exchange, or multiple-gluon exchange in the limit of a large number of colors, suggests that exotic states do not occur.[2]

This paper reports on a search for exotic mesons produced in the baryon-exchange reaction

$$\pi^+p \to \Lambda_f{}^0S^{++}. \tag{1}$$

The simplest quark diagram of this reaction is given in Fig. 1. The interest in baryon-exchange reactions is primarily based on two component duality schemes which suggest that exotic states

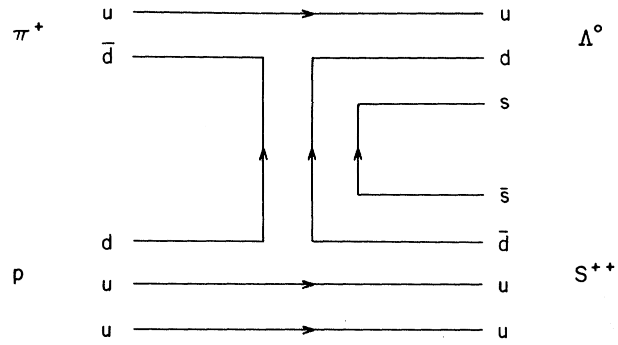

FIG. 1. Quark diagram for the baryon-exchange process $\pi^+p \to \Lambda_f{}^0 S^{++}$ studied in this experiment. The recoil S^{++} system is explicitly exotic.

might easily be produced in such reactions with cross sections comparable to normal states.

Previous high-sensitivity missing-mass experiments,[3,4] which use reaction (1) and the reaction $\pi^- n \to p_f X^{--}$, have set 95%-confidence-level upper limits for the production of exotic mesons with masses < 2.5 GeV/c^2 of 60–70 nb. Complete kinematical reconstructions of $\pi^- n \to p_f(\pi^-\pi^-)$ in Ref. 4 and $\pi^- n \to p_f(\bar{p}p\pi^-\pi^-)$ in Ref. 5 set 95%-confidence-level limits on the cross section times branching ratio (σB) of 8–20 nb.

Our experiment was performed at Brookhaven National Laboratory's Multiparticle Spectrometer (MPS) facility in a 9.8-GeV/c beam. It was designed to be sensitive to masses at or below the baryon-antibaryon threshold in order to improve on the earlier experimental limits. The trigger required at least three charged secondaries including a single, forward, positively charged particle with momentum > 5.5 GeV/c which did not fire an atmospheric Cherenkov counter. A system of cylindrical and planar spark chambers identified the tracks within the 1-T magnetic field of the MPS. Details of the apparatus may be found elsewhere.[6]

The analysis program paired the forward track with that negative track for which the effective mass, assuming $p_f\pi^-$, was closest to the Λ^0 mass. The point of closest approach of the two tracks determined the Λ^0 decay vertex while the primary vertex was determined from the other tracks. Figure 2 shows the $p_f\pi^-$ mass spectrum for those events having a neutral vee proper lifetime > 3 cm. Requiring $1.109 < M(p_f\pi^-) < 1.129$ GeV/c^2 selected $\sim 22\,200$ $\Lambda_f{}^0$ events over a background of ~ 2000 events. This yield is an order of magnitude increase in events over that of Ref. 3 for

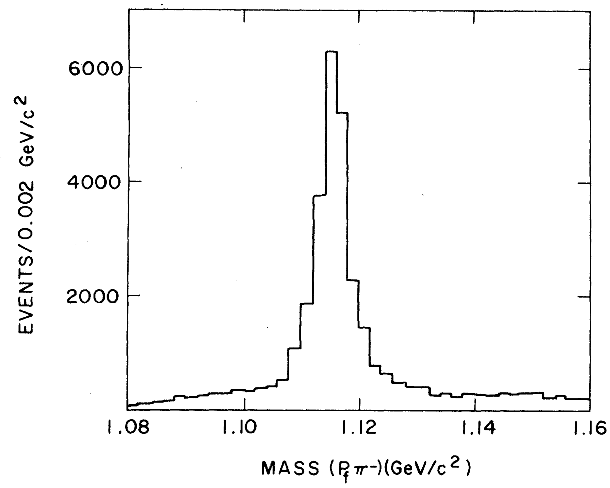

FIG. 2. The $p_f\pi^-$ effective-mass spectrum for those events with neutral vee proper lifetime > 3 cm.

$M(S^{++}) < 2.5$ GeV/c^2.

Figure 3(a) shows the missing mass squared ($M_X{}^2$) distribution against the $\Lambda_f{}^0$ for those events having two or less additional charged prongs. The falloff for $M_X{}^2 > 6$ (GeV/c^2)^2 is a result of the momentum selection on the forward particle. A smooth fourth-order polynomial fit in the region

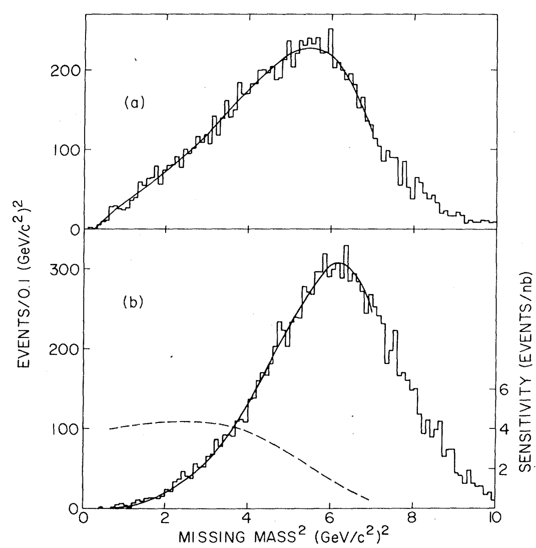

FIG. 3. Missing mass squared recoiling from the $\Lambda_f{}^0$: (a) for events having two or less additional tracks, and (b) for events having more than two additional tracks. The solid lines are smooth polynomial fits to the distributions. The dashed line in (b) gives the experimental sensitivity and refers to the scale on the right.

$0.3 < M_X^2 < 7.0$ $(\mathrm{GeV}/c^2)^2$ has a χ^2 of 56.8 for 62 degrees of freedom. The M_X^2 distribution for events having more than two additional charged tracks, Fig. 3(b), is also without significant structure. A smooth fifth-order polynomial fit from 0.7 to 7.0 $(\mathrm{GeV}/c^2)^2$ has a χ^2 of 55.2 for 57 degrees of freedom.

A Monte Carlo simulation determined the M_X^2 resolution and sensitivity. The calculated resolution varied from $\sigma = 0.13$ $(\mathrm{GeV}/c^2)^2$ at $M_X^2 = 1.0$ $(\mathrm{GeV}/c^2)^2$ to $\sigma = 0.07$ $(\mathrm{GeV}/c^2)^2$ at $M_X^2 = 6.25$ $(\mathrm{GeV}/c^2)^2$. The sensitivity, given by the dashed line in Fig. 3(b), was ≥ 4 events/nb for $M_X^2 \leq 4$ $(\mathrm{GeV}/c^2)^2$ with an overall uncertainty of $\pm 30\%$. Numerous checks on the Monte Carlo predictions are described in Ref. 6. The M_X^2 resolution was further checked by verifying that the position and width of the recoil p and π^+ signals observed in the M_X^2 distributions recoiling against either $K_f^+K^-\pi^+$ or $K_f^+K^-p$ agree with Monte Carlo simulations of the reaction $\pi^+p \to K_f^+K^-p\pi^+$. Taking into account the mass resolution, sensitivity, and overall normalization uncertainty, the 95%-confidence-level upper limit on the production of exotic resonances narrower than our mass resolution is < 20 nb for $M_X^2 \leq 4$ $(\mathrm{GeV}/c^2)^2$.

We also kinematically reconstructed the reaction

$$\pi^+p \to \Lambda_f^0K^+\pi^+. \quad (2)$$

While the momentum of the Λ_f^0 was well measured, the K^+ and π^+ tracks were often so short that only their angles were well determined. Therefore the magnitude of the momentum of each short track was calculated from the measured beam momentum, the Λ_f^0 momentum, and the angles of the short tracks, assuming a final state without neutral particles. Most of the events with missing neutral particles were eliminated by demanding that the momentum of the $K^+\pi^+$ system out of the plane of the beam and Λ_f^0 was ≤ 200 MeV/c. Under the hypothesis of reaction (2) the difference in energy between the final and initial states, ΔE, was calculated, as shown in Fig. 4. The Monte Carlo simulation of reaction (2) reproduced the width of the observed energy imbalance peak at $\Delta E = 0$ GeV. Requiring $-400 < \Delta E < 250$ MeV selected 690 events over a background of 80 events.

The $K^+\pi^+$ effective-mass spectrum is displayed in Fig. 5. The distribution is well fit by a smooth third-order polynomial over the range $0.65 < M(K^+\pi^+) < 2.9$ GeV/c^2 (χ^2 is 44.3 for 41 degrees of freedom). The Monte Carlo simulation indicated that the effective-mass resolution was $\sigma < 40$ MeV/c^2 over the mass range covered. The sensitivity, given by the dashed line in Fig. 5, was > 3 events/nb for $M(K^+\pi^+) < 2.0$ GeV/c^2. Figure 5 sets 95%-confidence-level limits for the production of narrow states in this channel of $\sigma B < 10$ nb for $M(K^+\pi^+) < 2.0$ GeV/c^2. We measure a total cross section for reaction (2) of 300 ± 100 nb for $M(K^+\pi^+) < 2.5$ GeV/c^2.

Finally we attempted to reconstruct the reaction

$$\pi^+p \to \Lambda_f^0 p \overline{\Sigma^-}, \quad \overline{\Sigma^-} \to \bar{n}\pi^+ \quad (3)$$

in the $\Lambda_f^0 + 2$ prong sample, since, as seen in Fig. 1, we are studying off-shell $p\overline{\Sigma^-}$ scattering. The

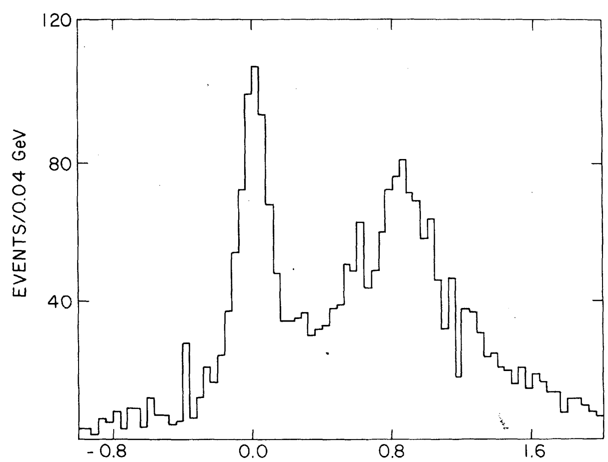

FIG. 4. Energy imbalance distribution of the Λ_f^0 + 2 prong events under the hypothesis $\pi^+p \to \Lambda_f^0K^+\pi^+$.

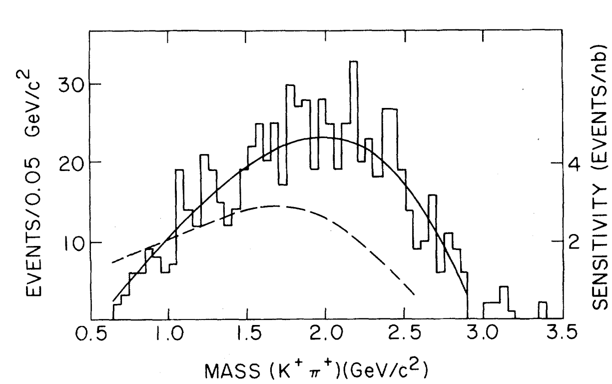

FIG. 5. $K^+\pi^+$ effective-mass spectrum of the events in Fig. 4 having energy imbalance between -400 and 250 MeV. The solid line is a smooth polynomial fit to the data. The dashed line gives the experimental sensitivity and refers to the scale on the right.

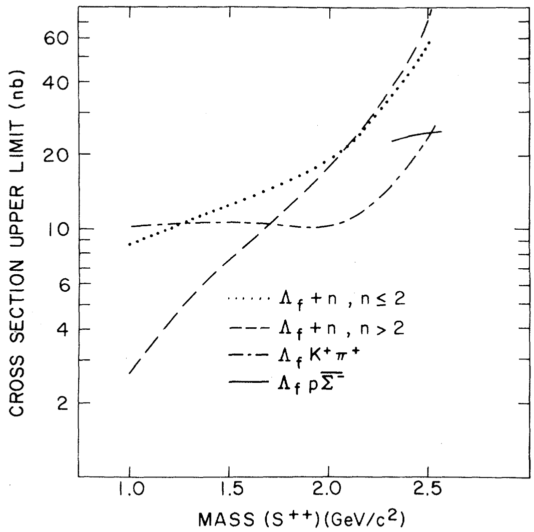

FIG. 6. 95%-confidence-level cross-section upper limits for the production of exotic S^{++} states in $\pi^+p \to \Lambda_f{}^0 S^{++}$.

Monte Carlo simulation indicated that the $\overline{\Sigma}^-$ would appear as a narrow bump in the missing-mass spectrum recoiling against the $\Lambda_f{}^0 p$. No clear signal was observed in the data.[7] The 95%-confidence-level upper limit of < 65 events corresponds to a total cross section for reaction (3) of < 90 nb for $M(p\overline{\Sigma}^-) < 3.0$ GeV/c^2. An examination of the $M_X{}^2$ distribution recoiling against the $\Lambda_f{}^0$ for those events satisfying the $\overline{\Sigma}^-$ selection established a 95%-confidence-level upper limit of < 20 nb on the production of narrow $p\overline{\Sigma}^-$ resonances with $M(p\overline{\Sigma}^-) < 2.5$ GeV/c^2.

The 95%-confidence-level cross-section upper limits for the production of narrow [full width at half maximum (FWHM) ≤ 0.2 (GeV/c^2)^2] exotic resonances in reactions (1), (2), and (3) are summarized in Fig. 6. Exotic states are expected to be produced with cross sections comparable to those of normal states in baryon-exchange processes.[1] While comparisons between different experiments sometimes involve factors of 2 or 3 in relative normalization uncertainties, for the purpose of comparison the cross section for the process $\pi^-p \to \Lambda_f{}^0 K^*$ is ~ 300 nb at 9.8 GeV/c (scaled from an 8-GeV/c result[3] by p^{-3}). Our experiment sets limits roughly an order of magnitude lower than this expectation and a factor of ~ 3 lower than previous limits. One may conclude that if explicitly exotic mesons exist, they either have anomalously small production cross sections in baryon-exchange reactions, or large widths.

The authors wish to thank the members of Brookhaven National Laboratory, Carnegie-Mellon University, and Southeastern-Massachusetts University who have contributed to various phases of this experiment. This work was supported in part by the U. S. Department of Energy and the National Science Foundation.

---

[a]Present address: Randall Laboratory, University of Michigan, Ann Arbor, Mich. 48109.

[b]Present address: Contravis Goerz Corporation, Pittsburgh, Pa. 15222.

[c]Present address: National Semiconductor (Israel), Hertzeliya, Israel.

[1]J. Rosner, Phys. Rev. Lett. 21, 950 (1968); R. Jaffe, Phys. Rev. D 17, 1444 (1978).

[2]G. 't Hooft, Nucl. Phys. B72, 461 (1974), and B75, 461 (1974); R. P. Feynman, in *Weak and Electromagnetic Interactions at High Energies*, edited by R. Balian and C. H. Llewellyn-Smith (North-Holland, Amsterdam, 1977), p. 120; E. Witten, Nucl. Phys. B160, 57 (1979).

[3]H. Brundiers *et al.*, Phys. Lett. 64B, 107 (1976).

[4]M. S. Alam *et al.*, Phys. Rev. Lett. 40, 1685 (1978).

[5]J. Boucrot *et al.*, Nucl. Phys. B121, 251 (1977).

[6]R. M. Bionta *et al.*, Phys. Rev. Lett. 44, 909 (1980).

[7]We were able to observe the recoil Σ^+ signal from the reaction $\pi^+p \to \overline{\Lambda}_f{}^0 p\Sigma^+$ in a sample of data taken with a forward antiproton trigger. Results on this reaction will be included in a future publication.