Service, Geneva, Switzerland, 1968), p. 173.

[2]R. Armenteros *et al.*, Phys. Lett. 28B, 521 (1969), and references therein.

[3]P. Eberhard, J. H. Friedman, M. Pripstein, and R. R. Ross, Phys. Rev. Lett. 22, 200 (1969).

[4]The results are presented for the combined data at 3.9 and 4.6 GeV/c. A similar analysis at each momentum separately shows results which are consistent with those obtained for the total sample.

[5]The film coverage is different for the two topologies.

[6]In each figure we indicate the sum of weights as well as the number of events.

[7]In order to investigate the reflections of the ρ we have performed a similar study after antiselection of $\Sigma\pi p$ events; the result of the present analysis remains the same.

[8]The minimization program used for the fits was the CERN program MINUIT, written by F. James.

[9]We have presented the analysis for only the $\Lambda(1405)\pi$ events of Reaction (1) because the large resonance signal-to-noise ratio allows less uncertainty in the estimation of the background. The study of the $\Sigma(1670) \to \Sigma^{\pm}\pi^{\mp}\pi^{+}$ produces a consistent result, as is easily seen by a comparison between Fig. 2(b) and Fig. 1(b); however, there is a larger systematic uncertainty in the background estimate.

[10]The separation of the $\Sigma^0\pi^+\pi^-$ and $\Lambda^0\pi^+\pi^-$ final states has been discussed by V. E. Barnes *et al.*, Phys. Rev. Lett. 22, 479 (1969).

[11]We also observe a different energy behavior of the $\Sigma\pi$ and $\Sigma\pi\pi$ resonance-production cross sections, suggesting the two-resonance hypothesis. The values obtained are

$$\sigma(\Sigma^0\pi^+) = 28 \pm 5\ \mu\text{b},$$

$$\sigma(\Sigma^+\pi^+\pi^-) = 22 \pm 4\ \mu\text{b at } 3.9\ \text{GeV}/c;$$

and

$$\sigma(\Sigma^0\pi^+) = 25 \pm 4\ \mu\text{b},$$

$$\sigma(\Sigma^+\pi^+\pi^-) = 7 \pm 3\ \mu\text{b at } 4.6\ \text{GeV}/c.$$

HEAVY-BOSON PRODUCTION IN $\bar{p}p$ MULTIPION ANNIHILATION AT 6.4 GeV/c

G. Alexander, I. Bar-Nir, S. Dagan, G. Gidal,* J. Grunhaus, A. Levy, Y. Oren, and J. Schlesinger
Department of Physics and Astronomy, Tel-Aviv University, Ramat Aviv, Israel
(Received 30 April 1970)

Production of heavy bosons is studied in $\bar{p}p$ six-prong annihilations at 6.94 GeV/c. Evidence is presented for the existence of a heavy boson with a mass of 3.035 GeV and a full width of 0.200 GeV decaying into four and six pions. The possible existence of another boson at 3.4 GeV is also discussed.

Most of our present knowledge on the heavy bosons has been obtained from the missing-mass spectrometer experiments. The heaviest bosons so far reported using this technique lie in the neighborhood of 3 GeV.[1,2] The difficulties of this method are the large background, possible reflection of baryon resonances, and the fact that one often does not detect the decay products of the resonances observed.

Ever since the discovery of the ω meson in $\bar{p}p$ multipion annihilations it was thought that this reaction was best suited to search for high-mass bosons. The absence of nucleons in the final state increases the available energy for boson production and eliminates the background from reflections of baryon resonances. In the present paper we study the multipion $\bar{p}p$ annihilation events at an incident momentum of 6.94 GeV/c with the aim of looking for heavy bosons decaying into four and more pions. These decay modes may be expected for heavy bosons having large spin values, since angular momentum barriers would inhibit their decay into a few low-spin particles. In addition, bosons of positive G parity having an unnatural J^P value must decay into at least four pions.

In particular we report on the reactions

$$\bar{p}p \to 3\pi^+3\pi^- \quad (117 \text{ events}), \quad \sigma = 0.25 \pm 0.03 \text{ mb}, \quad (1)$$

$$\to 3\pi^+3\pi^-\pi^0 \quad (735 \text{ events}), \quad \sigma = 1.57 \pm 0.11 \text{ mb}, \quad (2)$$

identified in a sample of 25 000 pictures of the 80-in. Brookhaven National Laboratory hydrogen bubble chamber exposed to a 6.94-GeV/c separated $\bar{p}$ beam from the alternating-gradient synchrotron.

The six-prong events were measured on conventional measuring machines and processed through the geometrical-reconstruction and kinematic-constraints programs TVGP and SQUAW. Ionization estimates were used to resolve ambiguities with special attention to contamination from nucleon-antinucleon production and K^+K^- annihilation events. The experimental details and general features of these reactions have been described elsewhere.[3,4]

In Fig. 1(a) we show the neutral ($Q = 0$) six-pion

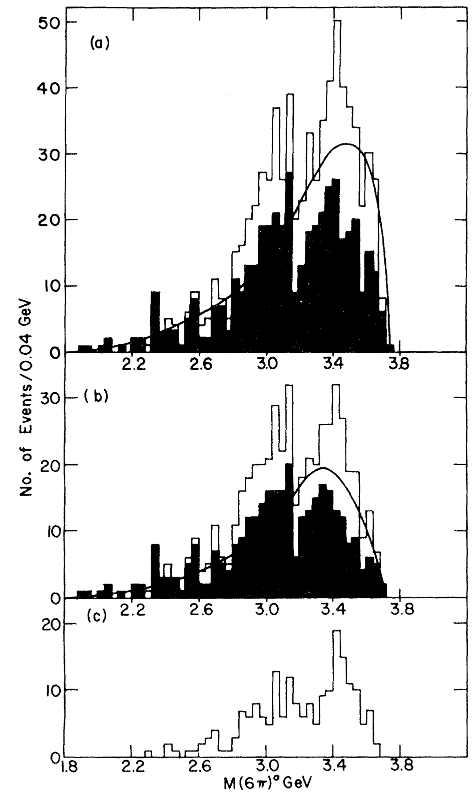

FIG. 1. Invariant-mass distributions of the $3\pi^+3\pi^-$ system in the reaction $\bar{p}p \to 3\pi^+3\pi^-\pi^0$. (a) All events and events with π^0 production angle of $|\cos\theta^*|>0.5$ (shaded area). The solid curve represents the LIPS distribution normalized to 70 % of the data as determined by the best fit; see Table I. (b) Same distributions as in (a) where events having $M(\pi^+\pi^-\pi^0)$ in the ω-meson mass band were removed. (c) Events with $|\cos\theta^*|<0.5$ and ω-meson mass band removed.

invariant-mass spectrum for Reaction (2). A common difficulty in searching for resonances in multipion final states in such mass plots is the frequent presence of more than one combination per event, while here we have only one combination per event. The solid curve in the figure represents Lorentz-invariant phase space (LIPS) normalized to 70% of the events, as determined by the best fit; see Table I. We see an enhancement in the 3-GeV region which we label as $X^0(3.0)$, and an excess of events at 3.4 GeV [$X^0(3.4)$] near the peak of phase space. The mass resolution calculated for this mass plot is ±18 MeV. A fit of the data by LIPS alone yields a confidence level of 0.002. To study this structure further we have looked at the production angular distribution of the recoiling π^0 meson. The enhancement at 3 GeV is produced predominantly in the forward and backward directions, while the enhancement in the 3.4-GeV region is produced isotropically [see Fig. 1(c)]. Thus, to decrease the background we show in the shaded area of Fig. 1(a) the mass plot for events with a production angle of $|\cos\theta^*|>0.5$. The $\pi^+\pi^-\pi^0$ mass spectrum in Reaction (2) shows a strong ω-meson signal approximately equal to the background. Hence we show in Fig. 1(b) the six-pion mass spectrum with the events in the ω mass band [$0.755 < M(\pi^+\pi^-\pi^0) < 0.815$ GeV] removed; again the shaded area corresponds to $|\cos\theta^*|>0.5$. The two X^0 enhancements are again clearly seen.

We have fitted the data to an incoherent mixture of LIPS and to simple Breit-Wigner resonances[5] and the results are shown in Table I. The fits assuming only the $X^0(3.0)$ are entirely adequate. The confidence levels are further improved when both resonances are included in the fits. The best values of the resonance parameters, in GeV, are

$$M = 3.035 \pm 0.025, \quad \Gamma = 0.200 \pm 0.060;$$
$$M = 3.420 \pm 0.020, \quad \Gamma = 0.100 \pm 0.60.$$

The statistical significance of the observed enhancements depends on the fit and is ~4.5 standard deviations for the 3-GeV and ~2.5 for the 3.4-GeV peak.

In an attempt to observe these resonances in other channels, we show in Fig. 2(a) the four-pion ($Q = 0$) invariant-mass spectrum for Re-

Table I. Results of best fit to LIPS only, LIPS + $X^0(3.0)$, and LIPS + $X^0(3.0)$ + $X^0(3.4)$, with the various cuts described in the text. "Conlev" signifies the confidence level of the fit.

	LIPS only	$X^0(3.0)$ + LIPS			$X^0(3.0)$ + $X^0(3.4)$ + LIPS			
Fitted sample	Conlev	% $X^0(3.0)$	% LIPS	Conlev	% $X^0(3.0)$	% $X^0(3.4)$	% LIPS	Conlev
All events	0.002	14 ± 4	86 ± 6	0.08	18 ± 4	10 ± 4	72 ± 7	0.3
$\|\cos\theta^*\|>0.5$	0.000 05	24 ± 6	76 ± 7	0.04	27 ± 6	9 ± 5	64 ± 10	0.08
ω cut	0.001	19 ± 5	81 ± 7	0.15	24 ± 5	10 ± 4	66 ± 8	0.33
ω cut and $\|\cos\theta^*\|>0.5$	0.002	26 ± 7	74 ± 8	0.12	30 ± 8	4 ± 5	66 ± 12	0.16

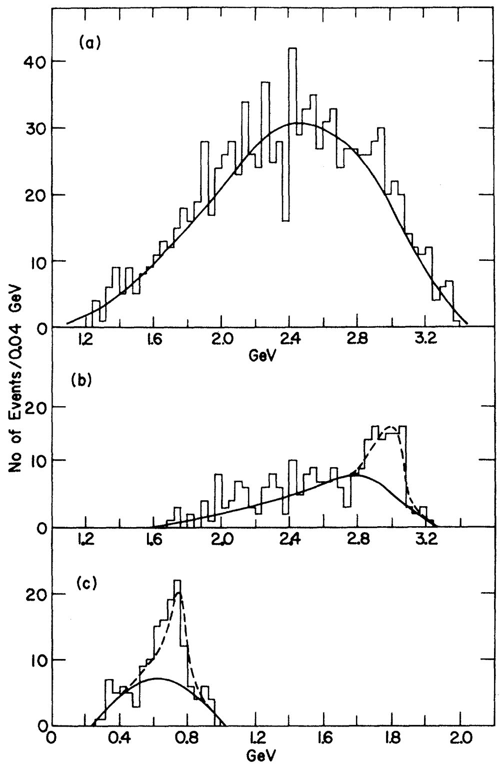

FIG. 2. Invariant-mass distributions of the reaction $\bar{p}p \to 3\pi^+3\pi^-$. (a) $M(4\pi)^0$ with nine combinations per event. The solid line represents the LIPS distribution. (b) $M(4\pi)^0$ where the recoiling $\pi^+\pi^-$ system lies in the ρ-meson mass band. The solid and dashed curves represent LIPS distribution and the $X^0(3.0)$ production as obtained by a fit, respectively. (c) $M(2\pi)^0$ for events where the recoiling $2\pi^+2\pi^-$ system is in the $X^0(3.0)$ mass region. The solid and dashed lines represent, respectively, LIPS distribution and ρ-meson production as obtained by a fit.

action (1). Here there are nine combinations per event, diluting possible signals with large background. No significant peak is seen near the 3.0-GeV mass value and the region of 3.4 GeV is already much supressed by phase space. To explore this channel in more detail we have studied the scatter plot of the four-pion ($Q = 0$) invariant-mass against the recoiling two-pion ($Q = 0$) invariant mass for the same reaction. In spite of the large background, an accumulation of events was seen at $M(4\pi) \simeq 2.9$ GeV, near the kinematical boundary. To illustrate this we show in Figs. 2(b) and 2(c), respectively, the recoiling two-pion mass spectrum for events lying in the four-pion enhancement [$2.84 < M(4\pi) < 3.08$ GeV] and the recoiling four-pion mass spectrum for events lying in the ρ mass band [$0.6 < M(2\pi) < 0.8$ GeV]. The solid curves are the predictions of LIPS. We clearly see enhancements in both spectra around 2.9 and 0.7 GeV. We interpret the latter as the ρ meson shifted to lower masses because of its proximity to the kinematical limit. The dashed curve in Fig. 2(b) represents a Monte Carlo simulation of the reaction $\bar{p}p \to X^0(3.0)\rho^0$, where the parameters of $X^0(3.0)$ were taken from the previous best fits to Reaction (2). Both the position and shape of the two peaks in Figs. 2(b) and 2(c) are well reproduced in a joint fit, yielding $(28 \pm 6)\%$ $X^0(3.0)\rho^0$ production and $(72 \pm 7)\%$ LIPS, with a confidence level of 0.16. Thus it is plausible that we are again observing the $X^0(3.0)$, this time produced together with a ρ meson. The four-pion ($Q = 0$) mass distribution in Reaction (2) has also been studied, but no signal of $X^0(3.0)$ was observed.

To investigate the isospin state of the $X^0(3.0)$ enhancement we have studied the six-pion charged ($Q = \pm 1$) mass spectrum in Reaction (2) and the results are shown in Fig. 3(a). The shaded area corresponds to events with $|\cos\theta^*| > 0.5$. No structure is seen in the region of 3.0 GeV; in fact, the LIPS distribution (solid line) reproduces the data well. It should be noted that the reflection of the $X^0(3.0)$ enhancement in this mass distribution is concentrated at the upper end. Since there are six combinations per event in this plot, the sensitivity of such a mass distribution to the presence of an $I = 1$ resonance has to be explored. If the $X^0(3.0)$ had an $I = 1$, then one would expect in the reaction $\bar{p}p \to X\pi$ at least twice as large a signal in the $Q = \pm 1$ system as in the $Q = 0$ system, provided the decay rates $X^0 \to 3\pi^+3\pi^-$ and $X^\pm \to 2\pi^+2\pi^-\pi^0\pi^\pm$ are comparable. In Fig. 3(b) we show a six-pion mass distribution generated in a Monte Carlo calculation using a distribution of 65% LIPS and 35% $\bar{p}p \to X\pi$ with the six combinations per event. The mass distribution is adequately described by LIPS (solid line) at the present statistical level of the experiment. Consequently, our data are not sensitive to any $Q = \pm 1$ component of an $I = 1$ resonance and no statement can be made on the isospin value of the $X^0(3.0)$ enhancement.

In conclusion, we have shown that statistically significant enhancements are seen in $\bar{p}p$ annihilation at a mass value of 3.035 GeV with a width of 0.2 GeV produced together with π^0 and ρ^0 mesons. Taken as a single resonance, the $X^0(3.0)$ has positive G parity and decays into four and six pions. Some indication is also seen for the existence of a resonance at 3.4 GeV decaying into six pions. However, the proximity of this enhancement to the peak of LIPS hinders a posi-

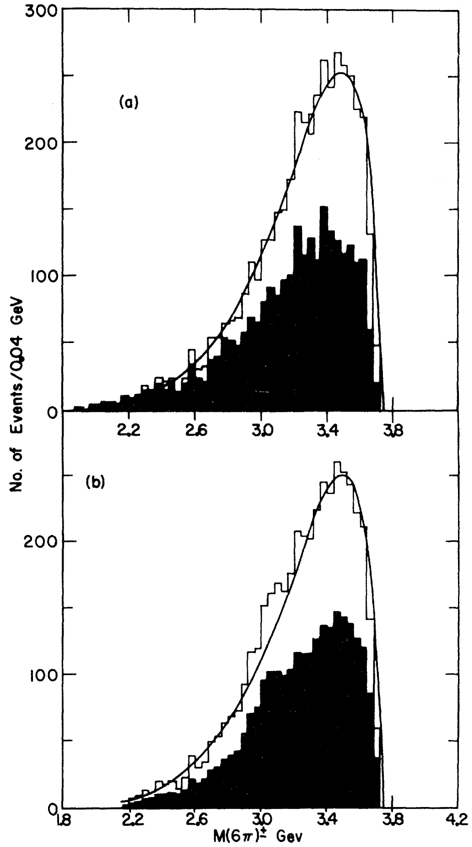

FIG. 3. $M(6\pi)^{\pm}$ distributions in the reaction $\bar{p}p \to 3\pi^+3\pi^-\pi^0$ with six combinations per event. Shaded areas correspond to events with production angle of $|\cos\theta^*|>0.5$; the solid curves represent LIPS distribution. (a) The experimental data. (b) Monte Carlo–generated events for a mixture of 65% LIPS and 35% $X^0(3.0)$ production (all events), and 46% LIPS + 54% $X^0(3.0)$ (shaded area). The mixtures are taken from the fits in Table I.

tive identification. Some evidence for a peak at 3.08 GeV has been reported in the four-pion ($Q = 0$) mass spectrum in the reaction $\bar{p}p \to 2\pi^+2\pi^-\pi^0$ at 5.7-GeV/c incident momentum.[6] The missing-mass experiments[1,2] have reported several negatively charged enhancements in the 3-GeV mass region. These of necessity have $I \geq 1$ and it is possible that we are observing unresolved groups of them. There also remains the possibility that the $X^0(3.0)$ observed in the present experiment is an $I=0$ object. While no direct measurement of the $X^0(3.0)$ spin is at present possible, the assignment of boson resonances to Regge trajectories indicates that the spin of $X^0(3.0)$ might be rather high; current estimates of trajectories favor spin values near $J=8$ ($I=0$) or $J=9$ ($I=1$) for mass near 3 GeV.[7]

We would like to thank Dr. R. Shutt, Dr. M. S. Webster, and the Brookhaven National Laboratory bubble chamber group for making the film available to us. We also wish to thank Dr. S. Nussinov for many helpful discussions. Finally we would like to acknowledge the valuable help of our technical and scanning staffs.

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*Permanent address: Lawrence Radiation Laboratory, University of California, Berkeley, Calif.

[1]For a recent summary on heavy bosons see, e.g., B. Maglić, in *Proceedings of the Lund International Conference on Elementary Particles*, edited by G. von Dardel (Berlingska Boktryckeriet, Lund, Sweden, 1970), p. 271.

[2]R. Baud *et al.*, Phys. Lett. 30B, 129 (1969); R. Baud *et al.*, to be published.

[3]T. Ferbel, J. A. Johnson, H. L. Kraybill, J. Sandweiss, and H. D. Taft, Phys. Rev. 173, 1307 (1968). In this paper a small sample of $\bar{p}p$ six-prong annihilation events from this exposure was analyzed and some general features were described.

[4]I. Bar-Nir, A. Brandstetter, S. Dagan, G. Gidal, J. Grunhaus, Y. Oren, J. Schlesinger, and G. Alexander, to be published.

[5]It is worthwhile to note that the LIPS distributions have been found to describe adequately the background of a large variety of mass plots in $\bar{p}p$ multipion annihilations at 6.94 GeV/c (see, e.g., Ref. 4).

[6]B. French, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968*, edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 91.

[7]See, e.g., M. Roos, Lett. Nuovo Cimento 3, 257 (1970).