Search for Charge −2 Mesons in the Reaction $\pi^- d \to (p_s) X^{--} p_{\mathrm{forward}}$ at 13.2 GeV/c

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A wide variety of final states are explored in the baryon exchange reactions $\pi^- d \to (p_s) X^{--} p_{\mathrm{forward}}$ and $\pi^- d \to (n_s) X^- p_{\mathrm{forward}}$, with a sensitivity of 240 events per microbarn per nucleon. We find no statistically significant evidence for charge − 2 exotic mesons or any other new structure over a mass range extending from below the nucleon-antinucleon threshold to about 3.2 GeV.

This Letter describes an experiment to search for doubly charged (exotic) mesons in the baryon-exchange reaction

$$\pi^- + d \to (p_s) + X^{--} + p_{\mathrm{forward}}, \tag{1}$$

at 13.2 GeV/c. The complementary reaction

$$\pi^- + d \to (n_s) + X^- + p_{\mathrm{forward}}, \tag{2}$$

permitted a simultaneous investigation of familiar nonexotic X^- states, as well as the possibility of identifying the charge − 1 components of potential charge − 2 states. The theoretical motivation for an exotic-meson search in a baryon-exchange reaction is that such states, assuming they consist of four quarks, should couple strongly to baryon-antibaryon channels. Furthermore, theoretical predictions along this line suggest that the level of exotic-meson production might be comparable with that of nonexotic-meson production.[1] Related experiments in this area,[2] and recent experimental and theoretical works suggesting the existence of baryon-antibaryon resonances,[3,4] make results of the kind presented here of particular current interest.

The experiment layout is displayed in Fig. 1. Interactions occurred in a 60-cm-long by 3.2-cm-diam target filled with liquid deuterium within the SLAC (Stanford Linear Accelerator Center) 2-m streamer chamber. The beam came in 1.5-μsec bursts with about four particles per burst and there were about 120 bursts per second. Beam pions had momenta of 13.2 GeV/c with good momentum ($\Delta P/P = \pm 0.5\%$) and angle ($\Delta\theta = \pm 1.2$ mrad) resolution. The forward proton momenta and angles were measured with comparable accuracy using downstream wire spark chambers in conjunction with the streamer chamber. The forward positive-particle momentum selection in the trigger was performed by a coincidence matrix using two scintillator hodoscope banks. A threshold-type Cherenkov counter included in the trigger distinguished forward protons from pions and kaons. The forward-proton acceptance includes angles with respect to the beam direction of less than about 50 mrad and momenta greater than 7.8 GeV/c, with maximal detection efficiency in the mass region between about 1.8 and 3.2 GeV, for the X^{--} or X^- systems. The trigger cross section, adding both Reactions (1) and (2), is about 60 μb and the sensitivity was about 240 events/μb per nucleon. An unusual feature of this experiment, made possible by use of the streamer chamber, was the ability to analyze rare complex multiparticle final states.

We obtained 120 000 triggers with photographs from the streamer chamber and complete records from the downstream spectrometer. The streamer chamber photographs of these events were scanned and measured on image plane digitizers and analyzed by means of conventional vertex reconstruction, space reconstruction, and kinematic fitting programs at the SLAC Computing Center. Coupling the streamer chamber and the spectrometer yielded 13 700 clean events which fulfilled our requirements. We analyzed only those

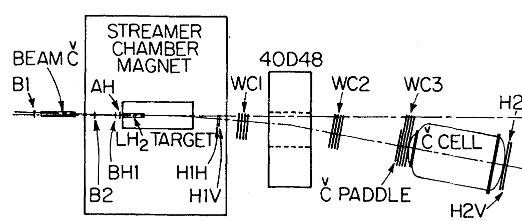

FIG. 1. Layout of SLAC streamer chamber experiment. Scale is given by the 2 m length of the streamer chamber. Beam defining counters are labeled B1, B2, BH1, AH; H1H, H1V, H2H, and H2V are the downstream hodoscope counters; WC1, WC2, and WC3 are wire spark chambers.

events with a single interaction in a beam burst in the streamer chamber and with a forward proton of momentum >7.8 GeV/c which extrapolated cleanly through the full downstream spectrometer. The momentum and angle of the forward proton, as measured in the downstream spectrometer, were integrated into the space reconstruction and kinematic fitting procedure.

We discuss results from two types of mass distributions in these data. One set of distributions (see Fig. 2) is obtained using the square of the missing mass recoiling against the forward proton and charged-particle multiplicities as determined from the streamer-chamber data. Full widths of the errors on the square of the missing mass due to the combined effect of the measuring resolution and the Fermi motion of the target are indicated by horizontal error bars in Fig. 2(c).

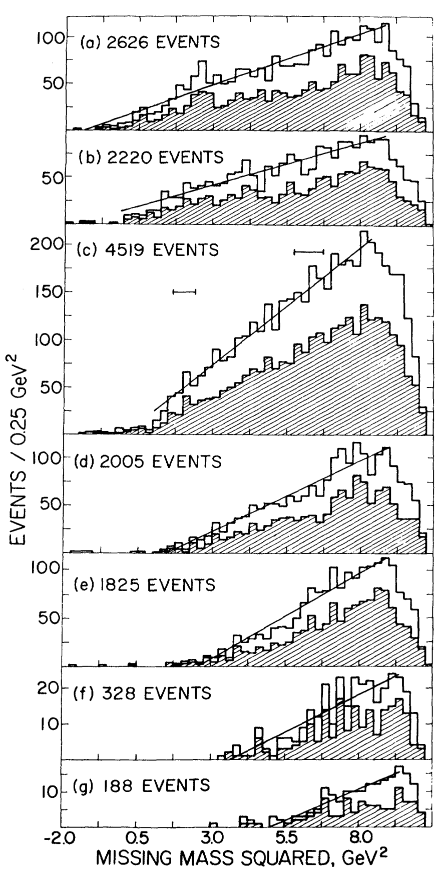

FIG. 2. Square of the missing mass (off p_{forward}) distributions, broken down according to final-state slow charged tracks (most events have missing neutrals). (a) (−); (b) (− −); (c) (− + −); (d) (− − + −); (e) (− + − + −); (f) (− − + − + −); (g) (− + − + − + −). Shaded histograms are with $|u'| < 0.16$ (GeV/c)^2.

Linear fits are shown as an indication of the background level.

The second set of distributions (see Fig. 3) is obtained from the smaller sample of events for which four-constraint[5] kinematic fits were made with confidence level above 4%. Comparison of these fits involving a spectator particle with those obtained in a small sample with hydrogen yielded good agreement in comparable channels.

In Fig. 2(a) where the X^- recoiling against the triggering proton yields a single visible negative track, a 4-standard-deviation bump corresponding to 0.2 μb above a linear background is seen near the known state $g^-(1680)$. This would imply a significant signal in Fig. 2(c), as the g^- decays predominantly to four-pion channels, including $\pi^+\pi^-\pi^-\pi^0$, but we observe no signal in that mode.

As our downstream Cherenkov counter pressure was set to optimally accept X^- and X^{--} states in the mass region of 1.8 through 3.2 GeV where baryonium (or exotic) states are thought to exist, we are biased against low-mass states. Knowing from other data that the $\rho^-(770)$ should be produced at our energy with about 0.25 μb, we may infer that the small peak seen at this mass in Fig. 2(a) is the ρ^-. Structures interpreted as A_1^- and A_2^- in the missing-mass experiment of Anderson *et al.*[6] are not seen at a significant level in the (−) or (−+−) modes, Figs. 2(a) and 2(c), or in the four-constraint channel, Fig. 3(b).

The remaining distributions of Fig. 2 do not show fluctuations from smoothness large enough to demand a new state. The shaded areas in Fig. 2 correspond to events with $|u'| < 0.16$ GeV^2 ($u' \equiv u - u_{\min}$) chosen to enhance two-body final states involving a forward proton.[7] These plots also show no striking new deviations from smoothness; the apparent g signal in Fig. 2(a) is still present.

The mass spectra from the four-constraint fits are given in Figs. 3(a)–3(g). The number of events in these exclusive channels is limited and rather than attempt to draw or fit smooth background curves, we compare these mass distributions with Monte Carlo generated transverse-momentum-damped phase-space curves.[8] Figures 3(a)–3(e) show, alternatively, the X^- and X^{--} mass spectra for two through six backward pions, respectively. The $\bar{p}p\pi^-$ and $\bar{p}p\pi^-\pi^-$ mass plots are given in Figs. 3(f) and 3(g), respectively. The pion channels are plotted in 50-MeV bins and those with $\bar{p}p$ pairs in 25-MeV bins. These bin sizes correspond roughly to the mass resolution, full width at half-maximum, for these final states.

Detailed studies of the $\pi^-\pi^-p_f$ and $\pi^-\pi^+\pi^-p_f$ final

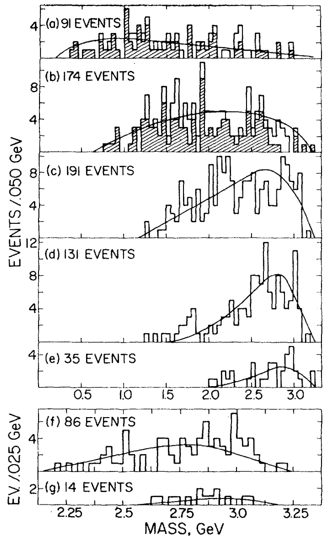

FIG. 3. Invariant-mass spectra from four-constraint fits. The smooth curves are predicted by the transverse-momentum-damped phase-space model (Ref. 8). (a) $M(\pi^-\pi^-)$ in $\pi^-\pi^- p_f$. Shaded histogram is with 1.5 GeV $< M(p\pi^-) <$ 1.75 GeV removed. (b) $M(\pi^-\pi^+\pi^-)$ in $\pi^-\pi^+\pi^- p_f$. Shaded histogram is with 1.5 GeV $< M(p\pi^-)$ $<$ 1.75 GeV removed. (c) $M(\pi^-\pi^-\pi^+\pi^-)$ in $\pi^-\pi^-\pi^+\pi^- p_f$. (d) $M(\pi^-\pi^+\pi^-\pi^+\pi^-)$ in $\pi^-\pi^+\pi^-\pi^+\pi^- p_f$. (e) $M(\pi^-\pi^-\pi^+\pi^-\pi^+\pi^-)$ in $\pi^-\pi^-\pi^+\pi^-\pi^+\pi^- p_f$. (f) $M(\bar{p}p\pi^-)$ in $\bar{p}p\pi^- p_f$. (g) $M(\bar{p}p\pi^-\pi^-)$ in $\bar{p}p\pi^-\pi^- p_f$.

states show that two-body production with forward $N^{*0}(1520, 1690) \rightarrow p_f\pi^-$ is an important mechanism. Hence, Figs. 3(a) and 3(b) are also plotted with 1.5 GeV $< M(p\pi^-) <$ 1.75 GeV removed.

Overall, the final states with backward pion production are described well by the phase-space curves and there are no striking enhancements. The excess of events at about 1.75 GeV above the smooth curve of the 5π channel shown in Fig. 3(d), as an indication of our sensitivity, corresponds to a cross section of about 0.06 μb.

A minor departure of the data from the phase-space curve occurs in the $\bar{p}p\pi^-$ final state, Fig. 3(f), where the mass distribution rises to a maximum near 2.95 GeV, a value where evidence for a narrow resonant state was reported in a 16-GeV/c $\pi^- p$ experiment involving forward-produced $\bar{p}p\pi^-$.[4] However, we observe that the $\bar{p}$ has, on the average, substantially higher momentum than the slow proton. (In the phase-space model, the $\bar{p}$ and the $p_{\rm slow}$ are on an equal footing.) Therefore, this departure from phase space may be due to $\bar{p}$ production occurring preferentially as some kind of breakup of the beam pion.

The $\bar{p}p\pi^-\pi^-$ final state [Fig. 3(g)] might be expected to be important in a search for $I=2$ states, but we find no evidence of structure. Our acceptance for such states produced with moderate u' dependence is good,[9] as is our mass resolution ($\simeq$ 25 MeV full width at half-maximum). We have produced in our experiment a total of only 14 events in this channel, all with $|u'| \lesssim 0.5$ GeV^2, corresponding to a cross section of less than 0.09 μb. Our negative results are consistent with the CERN omega experiment with similar event per microbarn sensitivity, but with different acceptance criteria.[2]

To conclude, no statistically significant evidence was seen in any of a wide variety of channels for charge -2 (or -1) mesons in the baryon-exchange reactions explored in this experiment. Our sensitivity was such that structures with cross sections times branching ratios comparable to that of backward $\rho^-(770)$, about 0.25 μb, should have been seen in the 1.8–3.2-GeV mass range where this experiment had maximum sensitivity.

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[4]C. Evangelista *et al.*, Phys. Lett. 72B, 139 (1977).

[5]Four-constraint fits of events with an unseen spectator were made by assuming the x, y, and z components of spectator momentum are zero with errors of $\pm$35 MeV/c on each component. Events with high-momentum spectator protons that were measurable in the streamer chamber made conventional four-constraint fits, but these were not included in the histograms as they might be expected to involve both target nucleons in the interaction processes.

[6]E. Anderson *et al.*, Phys. Rev. Lett. 22, 1390 (1969).

[7]Logarithmic dependence of $d\sigma/du'$ on u' has been observed in Reaction (2) (Ref. 6); i.e., $d\sigma/du' \simeq \exp(Bu')$, where $B \simeq 2.6$ for background events and $B \gtrsim 4$ for resonances. Consequently, a u' cut is expected to enhance resonance states relative to the background.

[8]The Lorentz-invariant phase space is weighted by the square of the matrix element proportional to $\exp(-B\sum p_{\perp,i}^2)$ where i extends over all final-state particles. The value of B is obtained by comparing $p_{\parallel}$ and $p_{\perp}$ distributions in the data, for all four-constraint final states, with the predicted distributions obtained with the Monte Carlo program. A value of $B = 2.5$ represents a good average value to describe most of the qualitative features of the data.

[9]Using $d\sigma/du' \simeq \exp(4u')$ for backward resonance production (see Ref. 7), we estimate that in accepting protons within 50 mrad of the beam direction, about 70% of possible resonances in this channel are included.

Test for the Existence of Effectively Stable Neutral Heavy Leptons

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I propose a test for the existence of stable or unusually long-lived neutral heavy leptons using a beam-dump experiment with precise timing. The technique can also be used to measure the lepton mass. Several reactions which can help to determine the couplings of such a lepton and can serve as new probes of hadronic structure are discussed.

An old and intriguing question in particle physics is the following: Are the only stable leptons the ones of which we are already aware, namely e and also , if massless, ν_e, ν_μ, and ν_τ, or are there others? From recent work on unified models of weak and electromagnetic interactions[1] there is indeed some reason to think that a stable neutral massive lepton may exist. Such an absolutely (or effectively) stable lepton will be denoted E^0. In this paper I shall propose a model-independent test for the existence of stable or unusually long-lived E^0's. I shall also outline the features of several reactions involving such leptons.

The test which I propose utilizes a beam dump followed by a massive electronic target calorimeter with muon and, ideally, also electron spectrometers. At present it is, we believe, the most, and probably the only, practical way to search for (effectively stable) E^0's. The crucial aspect of the experiment is the use of timing to an accuracy of ~1 nsec in order to discriminate between the arrival of massless and massive neutral leptons and to select the latter. Beam-dump experiments have been carried out in the past as a means of searching for a leptonic signal from short-lived hadrons, or for unstable leptons[2]; however, they have not used timing methods as proposed here. In particular, the searches of Ref. 2 for the decay $L^0 \to \mu^\pm\ (e^\pm) + \pi^\mp$ do not bear on my suggested test, which is sensitive to longer-lived leptons. Precise timing has been used previously in the experiment of Alspector *et al.*[3] to measure the difference in μ and ν_μ velocities, but this was not a beam-dump experiment and hence was not optimized to search for E^0's.

A beam-dump experiment is uniquely sensitive to the leptonic decay products of short-lived hadrons containing heavy quarks. These decays will yield ν_e, ν_μ, and, for sufficiently heavy hadrons, ν_τ. They may also yield stable or long-lived neutral heavy leptons. This possibility is present, independent of any specific models; however, in particular, the SU(3)$\otimes$U(1) theory[1] predicts that the lightest of the set of quarks heavier than c, viz. $Q = t$ or b, will decay 100% of the time into $\overset{(-)}{E}{}^0$'s: $t \to (d \text{ or } s) + (e^+ \text{ or } \mu^+) + E^0$ or $b \to u + (e^- \text{ or } \mu^-) + \bar{E}^0$. The production of heavy hadrons is Zweig suppressed relative to light hadrons; the suppression factor is roughly 10^{-3} for charm and correspondingly smaller for heavier quarks. This will be reflected in the $\overset{(-)}{E}{}^0$ flux. However, with the timing discrimination there are essentially no significant backgrounds to our suggested search; in particular $\overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu$, (massless) $\overset{(-)}{\nu}_\tau$, and muon halo do not constitute backgrounds. Thus the test is sensitive to a very small signal.

The proposed test makes crucial use of the rf structure of a pulse of protons from the accelerator. At Fermilab, a pulse consists of a large number of individual bunches of protons, each of width ~1 nsec, separated by 18.8 nsec. This rf structure is preserved by neutrinos from the dump, given the existing upper bounds on their